# UTILITY PATENT
## APPLICATION TRANSMITTAL
(Only for new nonprovisional applications
under 37 CFR 1.53(b))

| Attorney Docket No. | 990527 | Total Pages |
|---|---|---|

First Named Inventor or Application Identifier

**Akito KURAMATA, Shinichi KUBOTA, Kazuhiko HORINO and Reiko SOEJIMA**

Check Box, if applicable [ ] Duplicate

Express Mail Label No.

APPLICATION ELEMENTS FOR:
**OPTICAL SEMICONDUCTOR DEVICE HAVING AN EPITAXIAL LAYER OF III-V COMPOUND SEMICONDUCTOR MATERIAL CONTAINING N AS A GROUP V ELEMENT**

ADDRESS TO:  Assistant Commissioner for Patents
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1. [XX]  Fee Transmittal Form (Incorporated within this form)  **(The filing fee is deferred).**

2. [XX]  Specification          Total Pages [59]

3. [XX]  Drawing(s) (35 USC 113)          Total Sheets [20]

4. [ ]  Oath or Declaration          Total Pages  [ ]
   **Not attached; deferred under P. L. 97-247.**

   a. [ ]  Newly executed (original or copy)

   b. [ ]  Copy from prior application (37 CFR 1.63(d)
          (for continuation/divisional with Box 17 completed).

      i. [ ] <u>Deletion of Inventor(s)</u>
            Signed statement attached deleting inventor(s) named in prior application,
            see 37 CFR 1.63(d)(2) and 1.33(b).

5. [ ]  Incorporation by reference (useable if box 4b is checked)
        The entire disclosure of the prior application, from which a copy of the oath or declaration is supplied under Box 4b, is considered as being part of the disclosure of the accompanying application and is hereby incorporated by reference therein.

6. [ ]  Microfiche Computer Program (Appendix)

7. [ ]  Nucleotide and/or Amino Acid Sequence Submission (if applicable, all necessary)
   a. [ ]  Computer Readable Copy
   b. [ ]  Paper Copy (identical to computer copy)
   c. [ ]  Statement Verifying identity of above copies

**ACCOMPANYING APPLICATION PARTS**

8. [ ]  Assignment Papers (cover sheet and document(s))

9. [ ]  37 CFR 3.73(b) Statement (when there is an assignee)          [ ] Power of Attorney

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## PAGE 2 OF 3

10. [ ] English translation Document (if applicable)

11. [ ] Information Disclosure Statement      [ ] Copies of IDS Citations

12. [ ] Preliminary Amendment

13. [XX] Return Receipt Postcard (MPEP 503)

14. [ ] Small Entity Statement(s)      [ ] Statement filed in prior application
                                             Status still proper and desired.

15. [ ] Claim for Convention Priority      [ ] Certified copy of Priority Document(s)

     a. Priority of _____ application no. _____ filed on _____ is claimed under 35 USC 119.
        The certified copies/copy have/has been filed in prior application Serial No. _____.
        (For Continuing Applications, if applicable).

16. [ ] Other _____

17. If a CONTINUING APPLICATION, check appropriate box and supply the requisite information:

     [ ] Continuation    [ ] Division    [ ] Continuation-in-part (CIP)   of prior application no. _____/_____

| FEE TRANSMITTAL<br><br>The filing fee is calculated below | Number Filed | Number Extra | Rate | Basic Fee $760.00 |
|---|---|---|---|---|
| Total Claims | 24 - 20 | 4 | x $18.00 | 72.00 |
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| UTILITY PATENT APPLICATION TRANSMITTAL (Only for new nonprovisional applications under 37 CFR 1.53(b)) | Attorney Docket No. | 990527 |
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| | **PAGE 3 OF 3** | |

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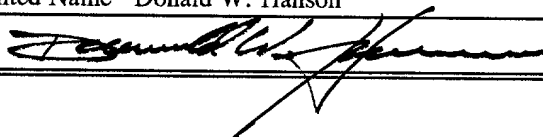
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SUBMITTED BY

| Typed or Printed Name   Donald W. Hanson | Reg. No.   27,133 |
|---|---|
| Signature | Date:   May 18, 1999 |

DWH/yap

SPECIFICATION

TO ALL WHOM IT MAY CONCERN:

BE IT KNOWN THAT WE, Akito Kuramata, a citizen of
Japan residing at Kawasaki-shi, Kanagawa, Japan, Shinichi
Kubota, a citizen of Japan residing at Kawasaki-shi,
Kanagawa, Japan, Kazuhiko Horino, a citizen of Japan
residing at Kawasaki-shi, Kanagawa, Japan and Reiko Soejima,
a citizen of Japan residing at Kawasaki-shi, Kanagawa, Japan
have invented certain new and useful improvements in

OPTICAL SEMICONDUCTOR DEVICE HAVING AN EPITAXIAL
LAYER OF III-V COMPOUND SEMICONDUCTOR MATERIAL
CONTAINING N AS A GROUP V ELEMENT

of which the following is a specification : -

1   TITLE OF THE INVENTION

OPTICAL SEMICONDUCTOR DEVICE HAVING AN
EPITAXIAL LAYER OF III-V COMPOUND SEMICONDUCTOR
MATERIAL CONTAINING N AS A GROUP V ELEMENT

5

BACKGROUND OF THE INVENTION

The present invention generally relates to
optical semiconductor devices and more particularly to
a GaN-family laser diode producing blue to ultraviolet
10  radiation and a fabrication process thereof.

Laser diodes, light-emitting diodes and
photodiodes are optical semiconductor devices used
extensively in the field of optical telecommunication,
optical information processing, recording of
15  information, and the like.

In the case of laser diode, there is a
demand, particularly in the field of optical
information recording, for a laser diode operable in
the optical wavelength band of blue to ultraviolet
20  radiation for increasing the recording density.  It
should be noted a laser diode oscillates generally in
the optical wavelength band of red to infrared
radiation.  Further, there is a demand for a
photodiode operable in such a short optical wavelength
25  band.

Conventionally, GaN, having a large bandgap,
has been recognized as a promising material for
constructing an optical semiconductor device such as a
laser diode or photodiode that operates in the
30  foregoing blue to ultraviolet wavelength band.  A
light-emitting diode using a GaN crystal for the
active layer thereof is already put into practical
use.  Further, a laser diode having a double
heterostructure of GaN/InGaN/GaN is already known.  By
35  incorporating an appropriate impurity element into the
GaN crystal, it is also possible to cause the laser
diode to oscillate in the visible wavelength band of

1     green radiation.

It should be noted that GaN has a Wurtzite
structure belonging to the hexagonal crystal system,
and the preparation of a single crystal substrate of
5     GaN is difficult.  Thus, the optical semiconductor
devices that use GaN for the active layer have been
constructed on the c-surface of a sapphire ($Al_2O_3$)
substrate, which also belongs to the hexagonal crystal
system.  Thereby, the GaN active layer is grown on the
10    foregoing c-surface of sapphire substrate epitaxially.

FIG.1 shows the construction of a
conventional GaN-family laser diode 1 operable in the
optical wavelength band of blue to ultraviolet
radiation.
15    Referring to FIG.1, the laser diode 1 is
formed on a sapphire substrate 11 and includes a GaN
buffer layer 12 formed on the substrate 11, an n-type
GaN electrode layer 13 formed on the GaN buffer layer
12, and a lower cladding layer 14 of n-type AlGaN
20    formed on the electrode layer with a composition of
$Al_{0.09}Ga_{0.91}N$.

On the lower cladding layer 14, there is
formed an optical waveguide layer 15 of n-type GaN,
and an active layer having a multiple quantum well
25    (MQW) structure is formed on the n-type optical
waveguide layer 15 epitaxially, wherein the MQW
structure includes a repetitive stacking of a unit
structure of undoped InGaN quantum well layer
sandwiched by a pair of undoped GaN barrier layers.
30    The active layer 15 is covered by an optical
waveguide layer 17 of p-type GaN, and an upper
cladding layer 18 of p-type AlGaN is formed on the
optical waveguide layer 17 with a composition of
$Al_{0.09}Ga_{0.91}N$.  The upper cladding layer 18 is formed
35    with an optical waveguide ridge 18A extending in the
axial direction of the laser diode at a laterally
central part thereof, and a contact layer 19 of p-type

1   GaN is formed on the top surface of the optical
    waveguide ridge 18A.

        The upper cladding layer 18 and the GaN
    contact layer 19, including both side walls of the
5   optical waveguide ridge 18A, are covered by an
    insulation film 20 of $SiO_2$, and a p-side electrode 21
    is formed on the insulation film 20 in electrical
    contact with the GaN contact layer at the optical
    waveguide ridge 18A via a via-hole formed in the
10  insulation film 20.

        The foregoing semiconductor layers 14 - 18
    form together a stacked layered structure defined by
    two vertical side walls $W_1$ and $W_2$ extending
    substantially vertically to the principal surface of
15  the substrate 11.  Further, there is formed an optical
    cavity in the stacked layered structure by a pair of
    mirror surfaces disposed so as to face in a direction
    perpendicularly to the sheet of FIG.1.

        Further, the substrate 11, buffer layer 12
20  and the electrode layer 13 thereon extend laterally
    beyond the foregoing side wall surface $W_2$, and an n-
    side electrode 22 is provided on the electrode layer
    13.  The laser diode of FIG.1 oscillates in the
    optical wavelength of 390 - 420 nm and has an
25  important application in the field of high-density
    information recording.

        The laser diode of FIG.1, however, has a
    drawback in that, due to the existence of large
    lattice misfit of as much as 13% or more at the
30  heteroepitaxial interface between the c-surface of the
    sapphire single crystal substrate 11 and the GaN
    epitaxial layer 12, the epitaxial layers 15 - 17
    forming the MQW structure 16 tend to include various
    crystal defects with a high concentration level.
35  Further, the laser diode 1 of FIG.1 has a difficulty,
    contrary to the conventional edge-emission type, in
    that formation of the electrode on the bottom surface

1    of the sapphire substrate 11 is difficult.  Thereby,
     the construction, and hence the fabrication process of
     the laser diode becomes inevitably complex.  In
     addition, the sapphire substrate used in the laser
5    diode 1 is difficult to be cleaved, and thus, it is
     difficult in the laser diode 1 to form the mirror
     surfaces by a conventional cleaving process, contrary
     to the conventional edge-emission type laser diode
     constructed on a substrate having a zinc blende
10   structure.

          In the laser diode 1 of FIG.1, the foregoing
     mirror surfaces are formed by a dry etching process,
     while such a process of forming the mirror surface by
     a dry etching process takes a substantial time.
15   Further, the quality of the mirror surfaces thus
     formed is inferior, in terms of flatness and angle, to
     the quality of the mirror surfaces formed by a
     cleaving process.

          It is also proposed to use a conductive SiC
20   substrate, which also belongs to the hexagonal crystal
     system, in place of the sapphire substrate and form
     the GaN-family active layer of the optical
     semiconductor on such an SiC substrate.  For example,
     the Japanese Laid-Open Patent Publication 10-135576
25   describes a technology of growing a GaN-family active
     layer on the (0001)Si surface of a 6H-SiC single
     crystal substrate epitaxially.  It should be note that
     use of an SiC substrate has various advantageous
     features such as small lattice misfit, less than 4%,
30   between the GaN active layer and the SiC substrate,
     electrical conductivity of the substrate, and
     excellent thermal conductivity of the substrate, which
     is superior to that of a sapphire substrate.  Thus, by
     using an SiC substrate, it is possible to construct a
35   laser diode oscillating in the optical wavelength of
     blue to violet radiation by using a construction
     similar to that of a conventional edge-emission type

1    laser diode.

In order to construct an optical
semiconductor device that uses a GaN-family active
layer formed on such an SiC substrate epitaxially, it
5    is necessary to establish a technology to form a GaN
buffer layer on the SiC substrate epitaxially.
Unfortunately, it is known that an epitaxial growth of
a GaN layer tends to lead to an island-like growth
when the growth is conducted on a SiC substrate. When
10   such an island-like growth occurs in the buffer layer,
it is difficult to form the GaN-family active layer
thereon with a planarized top surface. Further, the
GaN-family active layer thus formed tends to
incorporate therein various crystal defects, while
15   such crystal defects impedes the interaction occurring
in the active layer between GaN and photons. Thereby,
the efficiency of laser oscillation is deteriorated
seriously.

It is known that the problem of island-like
20   growth of GaN film is avoided when the SiC substrate
is covered by a buffer layer of AlN or AlGaN, such
that the desired epitaxial growth of the GaN active
layer occurs on such a buffer layer. However, it has
been not possible to provide electrical conductivity
25   to an AlN film used for the buffer layer.

When a buffer layer of AlGaN is used, on the
other hand, it is possible to provide an n-type
conductivity to the buffer layer, as long as the
content of Al in the AlGaN buffer layer does not
30   exceed 40%. Thus, as long as the composition of the
AlGaN layer is controlled as such, it is possible to
electrically interconnect the GaN active layer with
the SiC substrate via the AlGaN buffer layer.

On the other hand, the condition of forming
35   the conductive AlGaN epitaxial film on a SiC substrate
with a flat and smooth top surface suitable for
forming an active layer of GaN thereon, has not been

1 explored to the date.

## SUMMARY OF THE INVENTION

5 Accordingly, it is an object of the present invention to provide a novel and useful optical semiconductor device and a fabrication process thereof wherein the foregoing problems are successfully eliminated.

Another and more specific object of the 10 present invention is to provide an optical semiconductor device having an SiC substrate and a nitride layer of a group III element including Ga formed epitaxially on the substrate, wherein the epitaxial layer has a flat and smooth top surface and 15 that an excellent electrical interconnection is secured between the SiC substrate and the nitride epitaxial layer.

Another object of the present invention is to provide an optical semiconductor device having a 20 simple structure for confining the electric currents injected to the laser diode into a desired stripe region and is simultaneously capable of controlling the transverse mode oscillation in the state that laser diode produces a high-power optical output.

25 Another object of the present invention is to provide an optical semiconductor device having a selectively grown region of nitride and a fabrication process thereof.

Another object of the present invention is 30 to provide an optical semiconductor device having a nitride active layer of a group III element including Ga and an electron blocking layer provided for preventing overflowing of electrons from the active layer, wherein the doping of the electron blocking 35 layer is optimized such that crack formation is minimized, the carrier confinement in the active layer is maximized and the threshold voltage of laser

1 oscillation is minimized.

  Another object of the present invention is to provide an optical semiconductor device, comprising:

5  a substrate of SiC having a first conductivity type;

  a buffer layer of AlGaN formed on said substrate epitaxially, said buffer layer having said first conductivity type and a composition represented

10 as $Al_xGa_{1-x}N$;

  a first cladding layer having said first conductivity type, said first cladding layer being formed on said buffer layer epitaxially;

  an active layer formed epitaxially on said

15 first cladding layer;

  a second cladding layer having a second, opposite conductivity type, said second cladding layer being formed on said active layer epitaxially;

  a first electrode provided so as to inject

20 first-type carriers having a first polarity into said second cladding layer; and

  a second electrode provided on said substrate so as to inject second-type carriers having a second polarity,

25  said buffer layer containing said first type carriers with a concentration level from $3 \times 10^{18} cm^{-3}$ to $1 \times 10^{20} cm^{-3}$ and said compositional parameter x larger than 0 but smaller than 0.4 ($0 < x < 0.4$).

  According to the present invention, the

30 resistance at the interface between the substrate and the buffer layer is effectively minimized.

  Another object of the present invention is to provide an optical semiconductor device, comprising:

35  a substrate of SiC having a first conductivity type;

  a buffer layer of AlGaN formed on said

1     substrate epitaxially;

        a first cladding layer of AlGaN having said
first conductivity type, said first cladding layer
being formed on said buffer layer epitaxially;

5             an optical waveguide layer of GaN having
said first conductivity type, said optical waveguide
layer being formed on said first cladding layer
epitaxially;

        an active layer formed epitaxially on said

10    optical waveguide layer, said active layer containing
Ga as a group III element and N as a group V element;

        a second cladding layer of AlGaN having a
second, opposite conductivity type, said second
cladding layer being formed on said active layer

15    epitaxially;

        a first electrode provided so as to inject
first-type carriers having a first polarity into said
second cladding layer; and

        a second electrode provided on said

20    substrate so as to inject second-type carriers having
a second polarity,

        said substrate having a top surface
separated from a bottom surface of said active layer
by a distance of about 1.6 $\mu$m or more.

25        According to the present invention, the
threshold current of the optical semiconductor device
is successfully minimized.

        Another object of the present invention is
to provide an optical semiconductor device,

30    comprising:

        a substrate of SiC having a first
conductivity type;

        a first cladding layer having a first
conductivity type, said first cladding layer being

35    formed on said substrate epitaxially;

        an active layer formed epitaxially on said
first cladding layer;

a second cladding layer having a second, opposite conductivity type, said second cladding layer being formed on said active layer epitaxially;

a third cladding layer having said second conductivity type, said third cladding layer being formed on said second cladding layer epitaxially;

a first electrode provided so as to inject first-type carriers having a first polarity into said second cladding layer; and

a second electrode provided on said substrate so as to inject second-type carriers having a second polarity,

said third cladding layer having a ridge structure,

wherein an insulating film is interposed between said second cladding layer and said third cladding layer, said insulating film having an opening in correspondence to said ridge structure, with a width smaller than a width of said ridge structure.

According to the present invention, the injection of the drive current is made into an narrowly confined region of the ridge structure, and an efficient control is made on the laser oscillation of the horizontal transverse mode. As a result, the optical semiconductor device shows a smooth operational characteristic free from kink from a low-power state producing a low-power optical beam to a high-power state producing a high-power optical beam.

Another object of the present invention is to provide an optical semiconductor device, comprising:

a substrate of SiC having a first conductivity type;

a first cladding layer having a first conductivity type, said first cladding layer being formed on said substrate epitaxially;

an active layer formed epitaxially on said

1 first cladding layer;

  a second cladding layer having a second, opposite conductivity type, said second cladding layer being formed on said active layer epitaxially;

5  a third cladding layer having said second conductivity type, said third cladding layer being formed on said second cladding layer epitaxially;

  a contact layer of said second conductivity type, said contact layer being formed on said third

10 cladding layer;

  a first electrode provided on said contact layer;

  a second electrode provided on said substrate;

15  said third cladding layer forming a ridge structure having a T-shaped cross-section,

  said third cladding layer including, at a bottom part thereof, a pair of cuts, such that said cuts penetrate from respective lateral sides of said

20 ridge structure toward a center of said ridge structure.

  According to the present invention, the area of the insulation mask used in corresponding to the foregoing cuts when forming the third cladding layer

25 by a selective growth process is effectively minimized, and the formation of particles on the insulation film is minimized accordingly. As the insulation mask itself is removed after the selective growth process and before the step of forming the

30 first electrode, the problem of deterioration of adhesion caused in the first electrode as a result of the existence of the particles is successfully eliminated. As the third cladding layer thus formed has a T-shaped cross-section characterized by a

35 narrowly confined bottom part, the optical semiconductor device of the present invention is capable of injecting drive current selectively into

1    the ridge region.

Another object of the present invention is
to provide a method of fabricating an optical
semiconductor device, comprising the steps of:

5    forming an insulation pattern on a
semiconductor layer such that said insulation pattern
has an opening; and

forming, on said insulation pattern, a
regrowth region of a nitride of Al and a group III
10   element in correspondence to said opening,

said step of forming the regrowth region
being conducted by an metal-organic vapor phase
epitaxy process.

According to the present invention, it
15   becomes possible to form a regrowth region of a
nitride of Al and a group III element on the
insulation mask in correspondence to the opening
formed in the mask by using an MOVPE (metal-organic
vapor phase epitaxy) process. By using halogen
20   together with the gaseous source in the MOVPE process,
the formation of particles on the insulation mask is
minimized.

Another object of the present invention is
to provide an optical semiconductor device,
25   comprising:

a substrate;

a first cladding layer of a nitride of a
group III element formed epitaxially on said
substrate, said first cladding layer having an n-type
30   conductivity;

a first optical waveguide layer of a nitride
of a group III element formed epitaxially on said
first cladding layer, said first optical waveguide
layer having an n-type conductivity;

35   an active layer of a nitride of a group III
element formed epitaxially on said first optical
waveguide layer;

1        an electron blocking layer of a nitride of a group III element formed epitaxially on said active layer, said electron blocking layer having a p-type conductivity;

5        a second optical waveguide layer of a nitride of a group III element formed epitaxially on said electron blocking layer, said second optical waveguide layer having a p-type conductivity;

        a second cladding layer of a nitride of a

10    group III element formed epitaxially on said second optical waveguide layer, said second cladding layer having a p-type conductivity;

        a contact layer of a nitride of a group III element formed epitaxially on said second cladding

15    layer, said contact layer having a p-type conductivity;

        a first electrode provided on said contact layer; and

        a second electrode provided on said

20    substrate;

        each of said electron blocking layer, said second optical waveguide layer and said second cladding layer being doped by Mg;

        wherein said second optical waveguide layer

25    and said second cladding layer contain Mg therein with a concentration level lower than a concentration level of Mg in any of said electron blocking layer and said contact layer.

        According to the present invention, the

30    problem of cracking of the epitaxial layers in the optical semiconductor device is minimized. Further, the drive voltage of the optical semiconductor device is also minimized.

        Another object of the present invention is

35    to provide a semiconductor wafer, comprising:

        an SiC substrate having an n-type conductivity; and

1    an AlGaN layer having an n-type conductivity
formed on said SiC substrate with a composition
represented as $Al_xGa_{1-x}N$,

    wherein said AlGaN layer has a carrier
5 density in the range between $3 \times 10^{18} - 1 \times 10^{20} cm^{-3}$,
and

    wherein said compositional parameter x is
larger than 0 but smaller than 0.4 (0 < x < 0.4).

    According to the present invention, the
10 resistance at the interface between the SiC substrate
and the AlGaN buffer layer is minimized.

    Other objects and further features of the
present invention will become apparent from the
following detailed description when read in
15 conjunction with the attached drawings.


BRIEF DESCRIPTION OF THE DRAWINGS

    FIG.1 is a diagram showing the construction
of a conventional GaN-family laser diode;
20    FIGS.2A and 2B are diagrams showing the
experiments constituting one of the basis of the
present invention;

    FIG.3 is another diagram showing the
experiments constituting one of the basis of the
25 present invention;


    FIG.4 is another diagram showing the
experiments constituting one of the basis of the
present invention;
30    FIG.5 is another diagram showing the
experiments constituting one of the basis of the
present invention;

    FIGS.6A and 6B are diagrams showing the
construction of a laser diode according to a first
35 embodiment of the present invention;

    FIG.7 is a diagram showing the experiments
constituting one of the basis of the present

1      invention;

        FIG.8 is a diagram showing the construction of a laser diode according to a second embodiment of the present invention;

5         FIG.9 is a diagram showing a modification of the laser diode of FIG.8;

        FIGS.10A and 10B are diagrams showing the fabrication process of a laser diode according to a third embodiment of the present invention;

10         FIG.11 is a diagram showing a modification of the laser diode of the third embodiment;p

        FIGS.12A and 12B are diagrams showing the construction of a mask used in a selective growth process when fabricating the laser diode of the third

15 embodiment and a laser diode of a fourth embodiment of the present invention;

        FIG.13 is a diagram showing the construction of a laser diode according to the fourth embodiment of the present invention;

20         FIGS.14A - 14F are diagrams showing the fabrication process of a laser diode according to a fifth embodiment of the present invention;

        FIG.15 is a diagram showing a distribution of Mg in a conventional laser diode;

25         FIG.16 is a diagram showing the experiments constituting one of the basis of the present invention;

        FIG.17 is a diagram showing the experiments constituting one of the basis of the present

30 invention;

        FIG.18 is a diagram showing a Mg distribution used in a laser diode according to a sixth embodiment of the present invention;

        FIG.19 is a diagram showing a Mg

35 distribution according to a modification of the sixth embodiment.

1  <u>DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT</u>
   [FIRST EMBODIMENT]
        In the description hereinafter, the mixed
   crystal having the composition $Al_xGa_{1-x}N$ (0 < x < 0.4)
5  will be designated merely as AlGaN. When the AlGaN
   mixed crystal has a composition falling in the
   foregoing range (0 < x < 0.4), the doping of AlGaN is
   possible. Further, the AlGaN mixed crystal having
   such a composition can be grown on an SiC substrate
10 with a flat and smooth top surface. The epitaxial
   growth of the AlGaN mixed crystal is typically
   conducted by an MOVPE process, wherein the epitaxial
   layer thus formed shows a flat and smooth top surface
   when the deposition is made under a pressure of 100
15 Torr and the AlGaN mixed crystal contains Al with an
   atomic fraction x of 0.09 or more.
        Thus, it is possible to construct a GaN-
   family laser diode on an n-type SiC substrate covered
   by an n-type $Al_xGa_{1-x}N$ buffer layer, by depositing
20 desired epitaxial layers of GaN or a mixed crystal of
   GaN. The laser diode thus formed typically oscillates
   at the wavelength of 420 nm and has a threshold
   current of about 500 mA. While the laser diode thus
   formed oscillates at the desired blue to ultraviolet
25 wavelength band as is expected, the laser diode also
   has a drawback in that the threshold voltage necessary
   for laser oscillation is very large, as large as about
   22V. In view of the built-in potential of about 3V
   for the pn junction in a GaN crystal, the threshold
30 voltage of the laser diode should be about 4 - 5 V if
   the laser diode is fabricated properly. Thus, the
   foregoing threshold voltage of 22V is deemed
   excessively large for a GaN-family laser diode.
        The inventor of the present invention has
35 conducted a series of experiments on the AlGaN/SiC
   epitaxial system in the investigation forming the
   basis of the present invention, and discovered that

1      the foregoing large threshold voltage arises as a
result of large AlGaN/SiC interface resistance between
the SiC substrate and the AlGaN buffer layer.

      In view of the fact that the band structure

5      of SiC and AlGaN is not yet established to the date,
and further in view of the expected existence of
concentration of crystal defects at the interface
between the SiC substrate and the AlGaN buffer layer,
the theoretical approach for reducing the AlGaN/SiC

10     interface resistance is expected to be difficult.
Thus, the present invention explored the solution for
reducing the AlGaN/SiC interface resistance
experimentally.

      FIG.2A shows the construction of the sample

15     used in the experiment.

      Referring to FIG.2A, a bulk crystal ingot of
Wurtzite-type 6H-SiC, doped by N to the n-type and
grown by an improved Rayleigh process, was used for
forming an SiC substrate 1.  More specifically, the

20     SiC substrate 1 was formed from the foregoing 6H-SiC
bulk crystal ingot to have a thickness of about 200
μm, wherein the substrate 1 thus formed was defined by
a principal surface of (0001)Si having a surface area
of about 1 $cm^2$.  The foregoing (0001)Si principal

25     surface of the substrate 1 was then covered by a
buffer layer 2 of n-type AlGaN grown thereon
epitaxially by an MOVPE process with a thickness of
about 1 μm.  The AlGaN buffer layer 2 thus formed was
doped by Si to the n-type.  The MOVPE process for

30     forming the buffer layer 2 was conducted at the
substrate temperature of 1090°C while using the
gaseous sources of TMG (trimethylgallium), TEG
(triethylgallium), TMA (trimethylaluminum) and ammonia
($NH_3$) together with an impurity gaseous source of

35     monosilane ($SiH_4$).

      After the formation of the buffer layer 2, a
contact layer 3 of n-type GaN was grown further on the

1     buffer layer 2 by an MOVPE process with a thickness of
about 0.2 µm for reducing the contact resistance.

        After the formation of the contact layer 3,
a circular or stripe-shaped electrode 6 was formed on

5     the GaN contact layer for measurement of the AlGaN/SiC
interface resistance, more specifically the
resistivity, between the substrate 1 and the buffer
layer 2, and a Ni electrode 5 was provided on the
bottom principal surface of the substrate 1 so as to

10    cover the entirety thereof. It should be noted that
the electrode 6 has a stacked structure including a
lower layer of Ti and an upper layer of Al, wherein
the electrode 6 was formed to have a diameter of 30 -
90 µm when the electrode 6 has a circular shape. When

15    the electrode 6 has a stripe structure, the electrode
6 was formed of a stripe having a width of 2 - 15 µm
and a length of 300 - 900 µm.

        In the experiment, the carrier density was
changed variously in the n-type AlGaN buffer layer 2

20    and also in the n-type SiC substrate, in combination
with the Al content in the buffer layer 2 and the
pressure used in the MOVPE process.

        FIG.2B shows the interface resistivity at
the interface between the n-type SiC substrate 1 and

25    the n-type AlGaN buffer layer 2 for the case the
carrier density was changed, wherein the horizontal
axis of FIG.2B represents the n-type carrier density
($cm^{-3}$) in the AlGaN buffer layer 2 in a logarithmic
scale, while the vertical axis of FIG.2B represents

30    the AlGaN/SiC interface resistivity ($\Omega cm^2$) also in a
logarithmic scale. In the experiment of FIG.2B, the
carrier density in the SiC substrate 1 was set to 1 x
10 $^{17}cm^{-3}$ and the Al content x of the AlGaN buffer
layer 2 was set to 0.09 (x = 0.09).

35        Referring to FIG.2B, there are represented
the value of the AlGaN/SiC interface resistivity for
the structure of FIG.2A in which the carrier density

1     in the n-type AlGaN buffer layer 2 is changed from $1 \times 10^{17}cm^{-3}$ to $1 \times 10^{20}cm^{-3}$. In the construction of FIG.2A, it should be noted that the bulk resistance is negligible for the electrodes 5 and 6, the SiC

5     substrate 1, the AlGaN buffer layer 2 and the GaN contact layer 3. Further, the contact resistance of the electrode, more specifically the interface resistance at the interface between the AlGaN buffer layer 2 and the contact layer 3, is also negligible.

10     Thus, the resistance measured across the electrodes 5 and 6 fairly represents the AlGaN/SiC interface resistance between the SiC substrate 1 and the AlGaN buffer layer 2.

    As will be apparent from FIG.2B, the plot of

15     the resistivity reveals the existence of two lines $r_1$ and $r_2$. More specifically, the experimental points are aligned on a line $r_2$ having a gentle gradient in the range of the carrier density larger than about $5 \times 10^{18}cm^{-3}$, while the experimental points are aligned on

20     a more steeper line $r_1$ when the carrier density is lower than the foregoing value of about $5 \times 10^{18}cm^{-3}$.

    It should be noted that the gentle gradient of the line $r_2$ indicates that the change of the AlGaN/SiC interface resistivity is small when the

25     carrier density is changed. The existence of the two lines, $r_1$ and $r_2$, suggests that the physical phenomenon occurring in the range of the line $r_1$ may be different from the physical phenomenon occurring in the range of the line $r_2$. From FIG.2B, it will be

30     understood that a low interface resistivity is realized with reliability, by setting the carrier density in the n-type AlGaN buffer layer 2 to be larger than about $5 \times 10^{18}cm^{-3}$.

    In a GaN-family laser diode having a mesa

35     structure, the entire resistance of the epitaxial layers generally takes the value of about $10\Omega$. Thereby, it is desired and necessary that the

1  AlGaN/SiC interface resistance is substantially lower
   than the total resistance of the epitaxial layers.

   In the event each epitaxial layer has a size
   of 700 μm x 4 μm, the AlGaN/SiC interface resistance
5  can be positively reduced to be smaller than the
   resistance of the entire epitaxial layers, even when
   the carrier density in the epitaxial layers is in the
   order of 3 x $10^{18}$cm$^{-3}$. Thus, it is preferable to dope
   the n-type AlGaN layer 2 to have a carrier density of
10 about 3 x $10^{18}$cm$^{-3}$ or more, more preferable about 5 x
   $10^{18}$cm$^{-3}$ or more.

   In doping the n-type AlGaN buffer layer 2,
   it was discovered that there appears a large amount of
   crystal defects on the surface of the AlGaN layer 2
15 when the carrier density in the layer 2 is set larger
   than the value of 1 x $10^{20}$cm$^{-3}$. Due to the excessive
   formation of the crystal defects, experiment for
   measuring the interface resistivity was not possible
   in this case. Thus, it is preferable that the carrier
20 density in the n-type AlGaN buffer layer 2 does not
   exceed the foregoing value of about 1 x $10^{20}$cm$^{-3}$.

   In the foregoing experiments, the carrier
   density of the n-type AlGaN buffer layer 2 on the n-
   type SiC substrate 1 was changed variously, while in
25 the second-series experiments that follow the
   foregoing first-series experiments, the AlGaN/SiC
   interface resistivity was measured while changing the
   carrier density in the n-type SiC substrate 1
   variously. In the second-series experiments, the
30 composition of the n-type AlGaN buffer layer 2 was set
   to have an Al content x of 0.09 (x = 0.09) and the
   carrier density of 5 x $10^{18}$cm$^{-3}$.

   FIG.3 shows the result of measurement of the
   AlGaN/SiC interface resistivity for various carrier
35 densities in the n-type SiC substrate 1 in the range
   from 1 x $10^{17}$cm$^{-3}$ to 3 x $10^{19}$cm$^{-3}$, wherein the
   horizontal axis shows the carrier density (cm$^{-3}$)

1   represented in a logarithmic scale, while the vertical
    axis represents the AlGaN/SiC interface resistivity
    ($\Omega$cm) in a logarithmic scale.

         As can be seen clearly from FIG.3, the
5   experimental points are aligned on two lines $r_3$ and
    $r_4$. More specifically, the AlGaN/SiC interface
    resistivity is represented by the line $r_3$ in the range
    of the carrier density smaller than about $1 \times 10^{18}$cm$^{-3}$. In the range of the carrier density larger than
10  about $1 \times 10^{18}$cm$^{-3}$, on the other hand, the AlGaN/SiC
    interface resistivity is represented by the line $r_4$.

         In the second-series experiments, it was
    discovered that the quality of the SiC bulk crystal is
    deteriorated substantially when the carrier density
15  therein is increased beyond the value of $1 \times 10^{20}$cm$^{-3}$.
    Because of the poor quality of the SiC substrate 1,
    the experiment was not possible in the range of the
    carrier density exceeding the foregoing value of $1 \times
    10^{18}$cm$^{-3}$.

20       Summarizing above, it is concluded that the
    n-type SiC substrate 1 preferably has the carrier
    density in the range between about $1 \times 10^{18}$cm$^{-3}$ and $1
    \times 10^{20}$cm$^{-3}$. When the carrier density is reduced below
    the foregoing value of $1 \times 10^{18}$cm$^{-3}$, the AlGaN/SiC
25  interface resistance increases sharply. When the
    carrier density exceeds the value of $1 \times 10^{18}$cm$^{-3}$, on
    the other hand, the quality of the SiC substrate 1 is
    deteriorated.

         Next, in the third-series experiment, an
30  investigation was made on the effect of the Al content
    x in the n-type AlGaN buffer layer 2 on the AlGaN/SiC
    interface resistance. In the third-series experiment,
    the carrier density in the n-type SiC substrate 1 was
    set to about $1 \times 10^{18}$cm$^{-3}$ and the carrier density in
35  the n-type AlGaN buffer layer 2 was  set to about $5 \times
    10^{18}$cm$^{-3}$.

         FIG.4 shows the AlGaN/SiC interface

1    resistance of the n-type AlGaN buffer layer 2 for the
     case in which the Al content x of the buffer layer 2,
     represented as $Al_xGa_{1-x}N$, is changed variously,
     wherein the horizontal axis represents the
5    compositional parameter x in terms of atomic percent,
     while the vertical axis represents the AlGaN/SiC
     interface resistivity.

     As can be seen from FIG.4, the experimental
     points are aligned on two lines, $r_5$ and $r_6$, wherein
10   the AlGaN/SiC interface resistivity is represented by
     the line $r_5$ having a gentle gradient when the
     compositional parameter x is smaller than about 9%.
     When the compositional parameter x increased beyond
     the value of about 9%, on the other hand, the
15   interface resistivity is represented by the line $r_6$
     having a steeper gradient.  Further, the interface
     resistivity increases with the compositional parameter
     x representing the Al content in the AlGaN buffer
     layer 2 in any of the lines $r_5$ and $r_6$.  Thus, from the
20   result of FIG.4, it is preferable that the Al content
     x in the n-type AlGaN buffer layer 2 is set smaller
     than 9%.

     In the foregoing first through third series
     experiments, the formation of the n-type AlGaN buffer
25   layer 2 was conducted by an MOVPE process.  On the
     other hand, it is believed that a similar result would
     be obtained also when the buffer layer 2 is formed by
     other deposition process such MBE (molecular beam
     epitaxy), as the value of the interface resistivity is
30   primarily controlled by the band structure and the
     impurity concentration level.

     Conventionally, the epitaxial growth of a
     GaN layer or a mixed crystal layer of GaN has been
     conducted by setting the pressure to about 100 Torr
35   when the growth is made by MOVPE.  In the foregoing
     experiments, the inventor of the present invention has
     discovered that it is necessary to increase the Al

1    content x in the n-type AlGaN buffer layer 2, which is
grown directly on the SiC substrate 1, to be larger
than 8% in order to obtain a flat and smooth top
surface.  Further, the inventor of the present

5    invention has discovered that a flat and smooth top
surface can be obtained for the n-type AlGaN buffer
layer 2 even when the Al content x therein is smaller
than 8%, by reducing the pressure in the MOVPE
process.

10       FIG.5 shows the minimum Al content x needed
for obtaining a planar and smooth top surface for the
n-type AlGaN buffer layer 2, grown on the n-type SiC
substrate 1 by the MOVPE process, as a function of the
pressure used in the MOVPE process.  More in detail,

15    the horizontal axis of FIG.5 represents the pressure
represented in Torr, while the vertical axis
represents the minimum Al content x in terms of
percent.  In FIG.5, the horizontal axis and the
vertical axis are represented in a linear scale.

20       Referring to FIG.5, it will be noted that
the minimum Al content x needed for obtaining a flat
and smooth top surface for the AlGaN buffer layer 2
decreases gradually with decreasing pressure used in
the MOVPE process along a line $r_7$.  In other words,

25    the relationship of FIG.5 represents the fact that the
desired flat and smooth top surface can be obtained
for the n-type AlGaN buffer layer 2 even when the Al
content therein is small, by decreasing the pressure
in the MOVPE process.

30       In the representation of FIG.5, it should be
noted that the Al content in the vertical axis may
contain an error of about ±1%.  Thus, the deviation of
the experimental point for the pressure of 20 Torr
from the line $r_7$ may or may not be the result of the

35    error.  It should be noted that the experimental
points for the pressure of 100 Torr, 70 Torr and 50
Torr are aligned on the line $r_7$.

1       In the description hereinafter, it is noted
that the value x, indicative of the Al content in the
AlGaN buffer layer 2 and represented in terms of
percent, includes an error of about ±1%.

5       From the result of FIG.5, it is concluded
that the MOVPE process is conducted under a pressure
of about 90 Torr or less when to grow an AlGaN layer
on an SiC substrate with a flat and smooth top surface
and with an Al content of about 8%. In order to grow

10 a similar AlGaN layer with an Al content of about 6%,
on the other hand, it is preferable to conduct the
MOVPE process under a pressure of about 70 Torr or
less. Further, in order to grow a similar AlGaN layer
with an Al content of about 4%, it is preferable to

15 conduct the MOVPE process under a pressure of about 50
Torr or less. In order to grow a similar AlGaN layer
with an Al content of about 2%, it is preferable to
conduct the MOVPE process under a pressure of about 20
Torr or less.

20       In view of the foregoing experimental
results, it is possible to grow an n-type AlGaN buffer
layer on an n-type SiC substrate epitaxially such that
the AlGaN/SiC interface resistance is minimized and
simultaneously the AlGaN buffer layer has a flat and

25 smooth top surface. By growing epitaxial layers on
the SiC substrate thus covered by the buffer layer, it
is possible to form a GaN-family laser diode having a
reduced threshold voltage. As a result of the use of
the SiC substrate, it should be noted that the laser

30 diode includes the n-side electrode formed on the SiC
substrate, similarly to a usual edge-emission type
laser diode.

      FIGS.6A and 6B show the construction of a
GaN-family laser diode 100 based on the foregoing

35 experiments.

      Referring to FIG.6A, the GaN-family laser
diode 100 is constructed on an n-type 6H-SiC substrate

1   31 having a Wurtzite structure and defined by a
    (0001)Si top surface. The substrate 31 is doped by n
    to a carrier density of about $8 \times 10^{17} cm^{-3}$, for
    example.

5        On the foregoing (0001)Si surface of the
    substrate 31, there is provided an n-type epitaxial
    structure 30, and an active layer structure 40 is
    formed on the epitaxial structure 30. Further,
    another epitaxial structure 50 of the p-type is formed
10  on the active layer structure 40.

         It should be noted that the n-type epitaxial
    structure 30 includes a buffer layer 32 of n-type
    AlGaN having a composition of $Al_{0.09}Ga_{0.91}N$ grown
    epitaxially on the (0001)Si surface of the substrate
15  31, another buffer layer 33 of n-type GaN formed
    epitaxially on the buffer layer 32, a cladding layer
    34 of n-type AlGaN having a composition of
    $Al_{0.09}Ga_{0.91}N$ grown epitaxially on the buffer layer
    33, and an optical waveguide layer 35 of n-type GaN
20  grown epitaxially on the cladding layer 34. The
    buffer layer 32 of the n-type AlGaN may have a
    thickness of about 0.15 μm and is doped with Si to an
    impurity concentration level of about $8 \times 10^{18} cm^{-3}$.
    The buffer layer 33, in turn, has a thickness of about
25  0.1 μm and is doped with Si to an impurity
    concentration level of about $3 \times 10^{18} cm^{-3}$. Further,
    the cladding layer 34 of n-type AlGaN has a thickness
    of typically about 0.5 μm and is doped with Si to an
    impurity concentration level of about $3 \times 10^{18} cm^{-3}$.
30  The optical waveguide layer 35 of n-type GaN has a
    thickness of about 0.1 μm and is doped with Si to a
    concentration level of about $3 \times 10^{18} cm^{-3}$.

         The active layer structure 40 forms an MQW
    (multiple quantum well) structure formed of alternate
35  and repetitive stacking of a quantum well layer of
    undoped InGaN having a composition of $In_{0.15}Ga_{0.85}N$
    and a barrier layer of undoped InGaN having a

composition of $In_{0.03}Ga_{0.97}N$, wherein the quantum well layer typically has a thickness of about 4.0 nm while the barrier layer has a thickness of typically about 5.0 nm. In one example, the quantum well layer is repeated three times and there are provided four barrier layers in all in the MQW active layer structure 40.

The p-type epitaxial structure 50 includes an electron blocking layer 51 of p-type AlGaN having a composition of $Al_{0.18}Ga_{0.82}N$ grown epitaxially on the active layer structure 40, an optical waveguide layer 52 of p-type GaN formed epitaxially on the electron blocking layer 51, a cladding layer 53 of p-type AlGaN having a composition of $Al_{0.09}Ga_{0.91}N$ grown epitaxially on the optical waveguide layer 52, and a contact layer 54 of p-type GaN grown epitaxially on the cladding layer 53. The electron blocking layer 51 of p-type AlGaN has a large bandgap and blocks the electrons overflowing from the active layer structure 40 underneath.

Typically, the electron blocking layer 51 has a thickness of about 20 nm and is doped with Mg to an impurity concentration level of about $5 \times 10^{19} cm^{-3}$. The GaN optical waveguide layer 52, in turn, has a thickness of about 0.1 μm and is doped with Mg to an impurity concentration level of about $5 \times 10^{19} cm^{-3}$. Further, the cladding layer 53 of p-type AlGaN has a thickness of typically about 0.5 μm and is doped with Mg to an impurity concentration level of about $5 \times 10^{19} cm^{-3}$. The contact layer 54 of p-type GaN has a thickness of about 0.2 μm and is doped with Mg to a concentration level of about $5 \times 10^{19} cm^{-3}$. By providing the contact layer 54, the contact resistance of a p-side electrode provided thereon is reduced.

The foregoing epitaxial layers are grown on the SiC substrate 31 by MOVPE under a reduced pressure of about 100 Torr. In the MOVPE process, TMG or TEG

1   is used for the gaseous source of Ga, TMA is used for
    the gaseous source of Al, TMI (trimethylindium) is
    used for the gaseous source of In, and $NH_3$ is used for
    the source of N, together with the dopant gas of $SiH_4$
5   or biscyclopentadienyl magnesium ($Cp_2Mg$).

        The n-type SiC substrate 31 may be formed
    from a bulk crystal ingot of n-type SiC grown by an
    improved Rayleigh method that uses a seed crystal.

        It should be noted that the n-type epitaxial
10  structure 30 may be formed by conducting the MOVPE
    process at a substrate temperature of 1090°C with a
    growth rate of about 2 μm/H.  On the other hand, the
    MQW structure of the active layer structure 40 may be
    formed by conducting the MOVPE process at a substrate
15  temperature of 780°C with a growth rate of about 0.3
    μm/H.  Further, the p-type epitaxial structure 50 may
    be formed by conducting the MOVPE process at a
    substrate temperature of 1130°C with a growth rate of
    about 1 μm/H.

20      In the GaN-family laser diode 100 thus
    obtained, it should be noted that the AlGaN/SiC
    interface resistance at the interface between the n-
    type SiC substrate 31 and the n-type AlGaN buffer
    layer 32 is successfully suppressed in view of the
25  fact that the n-type AlGaN buffer layer 32 having the
    composition of $Al_{0.09}Ga_{0.91}N$ contains the n-type
    carriers with the carrier density of about $8 \times 10^{18} cm^{-3}$.  See the diagram of FIG.2B.  It should be noted
    that the thickness of the n-type SiC substrate 31 may
30  be reduced, from an initial thickness of about 200 μm,
    to about 100 μm by polishing the rear surface thereof.

        After the formation of the epitaxial
    structures 30, 40 and 50 on the Si substrate 31, the
    epitaxial structures are subjected to a dry etching
35  process and a mesa structure having a width of 3 - 5
    μm, typically 3.5 μm, is formed to extend in the axial
    direction of the laser diode with a height of about

1    0.4 μm. As a result of the mesa formation, there is
formed a refractive optical guide structure in the
cladding layer 53 wherein the optical guide structure
thus formed controls the transverse mode of laser
5    oscillation.

    After the mesa formation, an insulation film
61 of $SiO_2$ is formed so as to cover the mesa structure
thus formed in the cladding layer 53 and the contact
layer 54, followed by formation of a contact window in
10    the insulation film 61 so as to expose the contact
layer 54. The contact window thus formed may have a
width of 1 - 4 μm.

    After the step of formation of the contact
window, an n-side electrode 63 is formed on the SiC
15    substrate 31 by depositing a Ni layer, a Ti layer and
a Au layer consecutively on the bottom surface of the
SiC substrate. Further, a p-side electrode 62 is
formed on the mesa structure by depositing a Ni layer,
a Ti layer and a Au layer consecutively.

20    The structure thus obtained is then
subjected to a cleaving process in the direction
perpendicular to the elongating direction of the mesa
structure, in other words the axial direction of the
laser diode, to form a ridge-type cavity having a
25    length of about 700 μm as represented in FIG.6B. It
should be noted that the ridge-type cavity extends in
the <1Ī00> direction of the SiC substrate 31, while
the cleavage surface has an orientation of [1Ī00]. In
the structure of FIG.6B, mirrors HR are formed on the
30    cleaved surfaces.

    It was confirmed that the GaN-family laser
diode 100 thus formed oscillates at the optical
wavelength of 420 nm when driven by a pulse generator
at a frequency of 1 kHz - 10 kHz. Thereby, it was
35    observed that the threshold current is about 500 mA
and the threshold voltage is about 15V.

    For the sake of comparison, a laser diode

1    similar to the GaN-family laser diode 100 was
     fabricated in which the carrier density of the n-type
     AlGaN buffer layer 32 is set to $3 \times 10^{18} cm^{-3}$ while
     maintaining the composition of the buffer layer 32 to
5    $Al_{0.09}Ga_{0.91}N$. In this experiment, although it was
     confirmed that the laser diode oscillates at the
     optical wavelength of 420 nm, the threshold voltage
     has increased to 22V. The threshold current remained
     the same and took the value of 500 mA. The foregoing
10   result indicates that the threshold voltage of the
     laser diode is reduced from 22V to 15V, by increasing
     the carrier density in the n-type AlGaN buffer layer
     32 having the composition of $Al_{0.09}Ga_{0.91}N$ from 3 x
     $10^{18} cm^{-3}$ to $8 \times 10^{18} cm^{-3}$.
15       Further, another experiment was conducted by
     fabricating a laser diode similar to the laser diode
     100 except that the carrier density in the n-type SiC
     substrate 31 is increased from $8 \times 10^{17} cm^{-3}$ to 4 x
     $10^{18} cm^{-3}$.
20       It was confirmed that the laser diode thus
     formed oscillates at the optical wavelength of 420 nm
     similarly to the laser diode 100 and that the
     threshold voltage was decreased to 12V, indicating a
     further decrease by 3V as compared with the laser
25   diode 100. The threshold current remained the same.
         In view of the relationship of FIG.2B, it is
     expected that the threshold voltage may be decreased
     further by increasing the carrier density in the n-
     type AlGaN buffer layer 32. Further, the relationship
30   of FIG.4 indicates that the AlGaN/SiC interface
     resistance, and hence the threshold voltage of the
     laser diode, is reduced further by reducing the Al
     content in the AlGaN buffer layer 32 below the value
     of 0.09.
35       In order to maintain the flat and smooth
     surface for the AlGaN buffer layer 32 for the case in
     which the Al content is reduced, it is preferable to

conduct the MOVPE process for forming the AlGaN buffer
layer 32 under a reduced pressure environment, in view
of the relationship of FIG.5. For example, the buffer
layer 32 may be formed to have a composition
$Al_{0.04}Ga_{0.96}N$ in place of the composition of
$Al_{0.09}Ga_{0.91}N$ by conducting the MOVPE process under
the pressure of 40 Torr. Other epitaxial layers are
formed similarly to the case of the laser diode 100.

When the Si concentration level of $8 \times 10^{18}cm^{-3}$ is used in the n-type AlGaN buffer layer 32
in combination with the foregoing composition of
$Al_{0.04}Ga_{0.96}N$, it is expected that the threshold
voltage decreased to about 10V. By further reduction
of the Al content in the n-type AlGaN buffer layer 32,
the AlGaN/SiC interface resistance, and hence the
threshold voltage, would be reduced further.


[SECOND EMBODIMENT]

During the experimental investigation on the
GaN-family laser diode 100 described with reference to
FIGS.6A and 6B, the inventor of the present invention
has discovered a relationship shown in FIG.7 between
the threshold current and the thickness of the
epitaxial layers interposed between the SiC substrate
41 and the active layer structure 40, wherein the
vertical axis represents the threshold current density
of the laser diode while the horizontal axis
represents the total thickness of the epitaxial layers
interposed between the SiC substrate 31 and the active
layer structure 40.

Referring to FIG.7, the threshold current
generally decreases with increasing thickness in the
epitaxial layers interposed between the substrate 31
and the active layer 40 and that the decrease occurs
sharply until the total thickness of the epitaxial
layers reach the value of about 1.6 μm.

While the reason of this phenomenon is not

1     clearly understood, it is probable that the defect
density in the epitaxial layers decreases with
increasing total thickness of the epitaxial layers
between the substrate 31 and the active layer
5     structure 40.

     Thus, in view of the relationship of FIG.7,
it is concluded that the threshold current of the
laser diode can be reduced by increasing the total
thickness of the epitaxial layers interposed between
10    the substrate 31 and the active layer structure 40.
On the other hand, there arises a problem of cracking
in the epitaxial structure 30, 40 or 50 when the
foregoing total thickness is increased excessively,
probably due to the tensile stress caused as a result
15    of the difference in thermal expansion between the SiC
substrate 31 and the nitride epitaxial layers thereon.

     The inventor of the present invention has
discovered that the cracking of the epitaxial
structures is effectively suppressed by setting the Al
20    content y of the lower cladding layer 34 of n-type
AlGaN having a composition represented as $Al_yGa_{1-y}N$,
to be smaller than the Al content x of the foregoing
n-type AlGaN buffer layer 32, of which composition is
represented as $Al_xGa_{1-x}N$ (y < x). Further, the
25    inventor of the present invention has discovered that
the problem of cracking of the epitaxial layers is
further suppressed by setting the Al content z of the
upper cladding layer 53 of p-type AlGaN having a
composition represented as $Al_zGa_{1-z}N$, to be smaller
30    than the Al content y in the lower cladding layer 34
(z < y). It is believed that the foregoing
suppression of the crack formation in the epitaxial
layers is achieved as a result of cancellation of the
tensile stress, which is induced in the epitaxial
35    layer by the differential thermal expansion of the SiC
substrate 31 and the epitaxial layers, by a
compressive stress. It should be noted that the

1    foregoing compressive stress is induced in the
     epitaxial layers including the buffer layer 32 and the
     cladding layers 34 and 53 as a result of the
     difference in the lattice constant between the SiC
5    substrate 31 and the epitaxial layers thereon.

          FIG.8 shows the construction of a laser
     diode 200 according to a second embodiment of the
     present invention, wherein those parts corresponding
     to the part described previously are designated by the
10   same reference numerals and the description thereof
     will be omitted.

          Referring to FIG.8, the laser diode 200 has
     a construction in which the GaN buffer layer 33 is
     omitted, and the AlGaN buffer layer 32, the AlGaN
15   cladding layer 34 and the GaN optical waveguide layer
     35 are formed to have respective thicknesses of 1.0
     μm, 1.5 μm and 0.1 μm.  As a result, the total
     thickness of the epitaxial layers interposed between
     the SiC substrate 31 and the active layer structure 40
20   takes a value of 2.6 μm, and the threshold current
     density of laser oscillation 200 is reduced to about 7
     - 8 kA/cm$^2$.

          In the present embodiment, it should be
     noted that the lower cladding layer 34 of n-type AlGaN
25   contains Al with an atomic fraction y of 0.10 (y =
     0.10), while this value of the Al content y is smaller
     than the Al content x of 0.15 (x = 0.15) of the n-type
     AlGaN buffer layer 32.  Further, it should be noted
     that the upper cladding layer 53 of p-type AlGaN
30   contains Al with an atomic fraction z of 0.08 (z =
     0.08), while this value z of the Al content of the
     upper cladding layer 53 is smaller than the foregoing
     value y for the lower cladding layer 34.

          As a result of the foregoing construction,
35   the laser diode 200 of the present embodiment
     successfully eliminates the crack formation in the
     epitaxial layers.

1        Other features of the present embodiment are substantially the same as those of the laser diode 100 described previously and further description thereof will be omitted.

5        FIG.9 shows the construction of a laser diode 210 corresponding to a modification of the laser diode 210 of the present embodiment, wherein those parts corresponding to the parts described previously are designated by the same reference numerals and the

10   description thereof will be omitted.

In the present modification, the buffer layer 32, the cladding layer 34 and the optical waveguide layer 35 are formed to have respective thicknesses of 0.35 µm, 1.15 µm and 0.1 µm, thus

15   leading to the total thickness of 1.6 µm for the epitaxial layers interposed between the SiC substrate 31 and the active layer structure 40. In the present modification, the buffer layer 32 and the lower cladding layer 34 are formed to have the same Al

20   content of 0.10 for the compositional parameters x and y, while the upper cladding layer 53 contains Al with a reduced content of 0.08 for the compositional parameter z. Thereby, the problem of cracking of the epitaxial layers is suppressed effectively also in the

25   present modification.


[THIRD EMBODIMENT]

In the ridge-type laser diode 100, 200 or 210 described before, the control of transversal mode

30   laser oscillation in the active layer structure 40 is achieved by forming a mesa structure in the upper cladding layer 53 as explained before.

In the ridge-type laser diode having such a structure, it is necessary to form the mesa structure

35   to have a width of less than about 2 µm in order to achieve a satisfactory control of the transversal mode oscillation, while the formation of such a narrow mesa

1     structure has been difficult. Further, the foregoing
conventional ridge-type laser diode has a drawback in
that the contact area between the electrode 62 and the
contact layer 54 is reduced inevitably when the width

5     of the mesa structure is thus reduced below 2 μm. It
should be noted that the width of the contact window
formed in the $SiO_2$ film 61 is reduced together with
the width of the mesa structure, while formation of
such a very small contact window in the $SiO_2$ film 61

10    on the mesa structure raises various problems.

       Further, the ridge-type laser diodes have a
further drawback in that the confinement of the
optical radiation inside the active layer structure 40
in the vertical direction tends to become weak and

15    insufficient. In order to realize a satisfactorily
strong optical confinement in the active layer
structure 40, it is necessary to increase the
thickness of the upper cladding layer 53 further,
while such an increase of thickness of the upper

20    cladding layer 53 tends to cause a cracking therein.
It should be noted that the cladding layer 53 has a
lattice constant different from that of the buffer
layer 32. In view of insufficient optical confinement
in the active layer structure 40, the ridge-type laser

25    diodes including the laser diodes 100, 200 and 210
tend to show the problem of optical loss caused by the
electrode 62 or poor far-field pattern (FFP) in the
optical beam produced by the laser diode.

       FIGS.10A and 10B show a fabrication process

30    of a laser diode 300 wherein the foregoing problems
are eliminated, wherein those parts corresponding to
the parts described previously are designated by the
same reference numerals and the description thereof
will be omitted.

35       Referring to FIG.10A, the laser diode 300 is
constructed on the n-type SiC substrate 31 carrying
thereon the n-type epitaxial structure 30, the active

1     layer structure 40 and the p-type epitaxial structure
50 similarly to the laser diodes of the previous
embodiments, wherein the mesa formation in the upper
cladding layer 53 or the contact layer 54 forming a

5     part of the p-type epitaxial structure 50 is omitted.
It should be noted that the n-type epitaxial structure
30 includes the n-type nitride layers 32 - 35 while
the p-type epitaxial structure includes the p-type
nitride layers 51 - 54 similarly as before. As a

10    result, the contact layer 54 has a flat top surface
and an insulation film 301 of $SiO_2$ is formed on the
flat top surface of the contact layer 54 by a high-
temperature CVD process with a thickness of about 300
nm.

15         The $SiO_2$ film 301 is then patterned by a
photolithographic process using HF as an etchant to
form a stripe opening 301W in the $SiO_2$ film 301 with a
width of about 1 μm, wherein the stripe opening 301W
is formed so as to extend in the axial direction of

20    the laser diode 300 coincident with the <1$\bar{1}$00>
direction of the SiC substrate 31.

        Next, in the step of FIG.10B, the deposition
of a p-type AlGaN layer having a composition of
$Al_{0.09}Ga_{0.91}N$ is made on the exposed part of the GaN

25    cap layer 54 exposed at the foregoing stripe opening
301W by an MOVPE process while using the $SiO_2$ film 301
as a mask, to form a third cladding layer 302 with a
thickness of about 1.4 μm. It should be noted that
the MOVPE process is conducted under a condition

30    similar to the condition used for forming the
epitaxial layers in the p-type epitaxial structure 50.
The third cladding layer 302 thus grow not only in the
upward direction but also in lateral directions to
form a ridge structure covering the insulation film

35    301 and extending thereon in the axial direction of
the laser diode.

        Next, in the step of FIG.10B, a contact

1    layer 303 of p-type GaN is formed on the third
     cladding layer 302 by an MOVPE process with a
     thickness of about 0.2 µm so as to cover both side
     walls and a top surface thereof continuously, and the
5    electrode 62 is deposited so as to cover the contact
     layer 303 continuously over a part corresponding to
     the side walls and the top surface of the underlying
     third cladding layer 302.  Further, the bottom surface
     of the n-type SiC substrate 31 is polished and the
10   electrode 63 is formed on the bottom surface of the
     SiC substrate 31 thus polished, similarly to the
     embodiments described before.

          According to the laser diode 300 of the
     present embodiment, the photolithographic patterning
15   process of the insulation film 301 is conducted in the
     step of FIG.10A on the flat, planar principal surface
     of the GaN cap layer 54.  Thereby, the patterning
     process is under an ideal condition with an excellent
     precision and the stripe opening 301W is formed
20   relatively easily to have a width of less than 1 µm.

          In the present embodiment, it should be
     noted that the cap layer 54 of GaN is provided for
     preventing the oxidation of the AlGaN cladding layer
     53 when forming the insulation film 301.  The
25   insulation film 301 is by no means limited to $SiO_2$ but
     other materials such as SiN or $Al_2O_3$ may also be used.

          It should be noted that the structure of the
     present embodiment is applicable also to the
     conventional laser diode constructed on a sapphire
30   substrate such as the one described with reference to
     FIG.1.  When using a sapphire substrate, the stripe
     opening 301W is formed in the insulation film 301 so
     as to extend in the <11Z0> direction of the sapphire
     substrate corresponding to the <1Ī> direction of a GaN
35   crystal.

          According to the laser diode 300 of the
     present embodiment, in which the electrode 62 covers

1　the top surface and both side walls of the third
cladding layer 302 continuously via the contact layer
303, the contact resistance of the electrode 62 is
reduced substantially.  Further, in view of the fact
5　that the injection of carriers (holes) into the active
layer structure 40 is restricted to the foregoing
elongating stripe opening 301W, the desired current
confinement in the active layer structure 40 is
achieved effectively without restricting the width of
10　the cladding layer 302 strictly.  Thereby, an
effective control of the transverse mode becomes
possible.

　　As the cladding layer 302 is formed as a
result of the selective growth of the AlGaN layer
15　occurring in the narrowly confined stripe opening
301W, there occurs no substantial problem of
relaxation of crystal lattice in the AlGaN cladding
layer 302 and the crack formation does not occur in
the cladding layer 302 even when the third cladding
20　layer 302 is formed to have an increased thickness.
Thereby, an excellent optical confinement is realized
in the vertical direction and the far-field pattern of
the laser diode is improved substantially.  Further,
the problem of optical loss caused by the electrode 62
25　is also reduced.

　　In the step of FIG.10B, there may be a case
in which particles are formed on the insulation film
301 during the process of forming the cladding layer
302 or the contact layer 303 by the selective growth
30　process.  It should be noted that the insulation film
301 is used in the foregoing selective growth process
as a mask.  When there occurs such a deposition of
particles on the insulation film 301, the adherence of
the electrode 62 may be deteriorated.

35　　In order to avoid the foregoing risk of
deterioration of adherence of the electrode 62, the
$SiO_2$ film 301 may be removed by a wet etching process

after the formation of the cladding layer 301 and the contact layer 303 by using a suitable etchant such as HF. As a result of removal of the $SiO_2$ film 301, the particles deposited thereon are also removed.

FIG.11 shows the construction of a laser diode 310 thus formed according to a modification of the present embodiment.

Referring to FIG.11, the third cladding layer 302 has a T-shaped form having a reduced width at the bottom part thereof similarly to the structure of FIG.10B, wherein it should be noted that the $SiO_2$ film 301 of FIG.10B is replaced with an air gap 301G cutting into the cladding layer 302 from both lateral sides thereof at the bottom part of the cladding layer 302. Further, an $SiO_2$ film similar to the $SiO_2$ film 61 is provided so as to cover the top surface and both side walls of the cladding layer 302 wherein the $SiO_2$ film 61 covers the exposed top surface of the contact layer 54. The contact laser 61 is formed with an opening exposing the GaN contact layer 303 covering the top surface of the third cladding layer 302 and the electrode 62 makes an ohmic contact with the exposed top surface of the third cladding layer 302.

Typically, the $SiO_2$ film 61 is formed by a vapor phase deposition process such as a high-temperature CVD process and may penetrate into the air gap 301G. Thereby, the air gap 301G may be filled entirely or partially by $SiO_2$ forming the $SiO_2$ film 61.

In the laser diode 300 or 310 of the present embodiment, it is possible to eliminate the contact layer 303.

[FOURTH EMBODIMENT]

FIG.12A is a plan view showing the insulation film 301 used as a mask in the foregoing fabrication process of the laser diode 300 or 310,

1    when forming the cladding layer 302 or 303 by a
     selective growth process.

          Referring to FIG.12A, the insulation film
     301 includes a number of linearly extending stripe
5    openings each having a width of about 1 μm.  The
     stripe openings are repeated with an interval of about
     300 μm, and thus, there is formed a wide area of $SiO_2$
     between one stripe opening and an adjacent stripe
     opening.

10        Thus, it will be easily understood that
     there occur an extensive formation of particles on the
     mask when the insulation film 301 of FIG.12A is used
     for the mask during the MOVPE process for forming the
     third cladding layer 302 or the contact layer 303.

15        In the present embodiment, the foregoing
     problem of deposition of particles on the mask is
     eliminated by using a mask 301A shown in FIG.12B.

          Referring to FIG.12B, it will be noted that
     a pair of linearly extending insulation stripes 301a
20   and 301b each having a width of 6 μm are disposed
     adjacent with each other to form a mask pattern 301c,
     with a gap 301n of about 1 μm formed between the
     insulation stripes 301a and 301b forming the mask
     pattern 301c, wherein the foregoing mask pattern 301c
25   thus formed is repeated a number of times with a pitch .
     of 300 μm.  In the mask 301A thus including the
     repetition of the mask patterns 301c, it should be
     noted that the underlying GaN contact layer 54 is
     exposed between a mask pattern 301c and an adjacent
30   mask pattern 301c, and the problem of particle
     formation is effectively eliminated.  Instead of
     forming particles, the source elements supplied during
     the MOVPE process for forming the p-type AlGaN
     cladding layer 302 or the p-type GaN contact layer 303
35   form an epitaxial layer of p-type AlGaN or p-type GaN
     on the exposed surface of the GaN contact layer 54.

          FIG.13 shows the construction of a laser

1    diode 400 that uses the mask 301A of FIG.12B for the
     selective growth process of the third cladding layer
     302 and the contact layer 303 according to a fourth
     embodiment of the present invention, wherein those
5    parts corresponding to the parts described previously
     are designated by the same reference numerals and the
     description thereof will be omitted.

     Referring to FIG.13, the mask 301A is formed
     on the contact layer 54 of p-type GaN, and the
10   cladding layer 302 of p-type AlGaN and the contact
     layer 303 of p-type GaN are formed consecutively on
     the contact layer 54 in correspondence to the stripe-
     formed gap 301n of the mask pattern 301c, by
     conducting the MOVPE process while using the mask 301A
15   as a mask.  Simultaneously, an epitaxial layer 302A of
     p-type AlGaN having a composition substantially
     identical with the composition of the cladding layer
     302 is formed outside the mask pattern 301c, and
     another epitaxial layer 303A of p-type GaN having a
20   substantially identical composition with the
     composition of the contact layer 303 is formed on the
     epitaxial layer 302A.  Thereby, the epitaxial
     structure including the epitaxial layers 302A and 303A
     is separated from the structure formed of the third
25   cladding layer 302 and the contact layer 303 by a
     recess exposing the mask 301A.

     It should be noted that the epitaxial layer
     303A is covered by another $SiO_2$ film 304, wherein the
     $SiO_2$ film 304 includes an opening formed in
30   correspondence to the recess part so as to expose the
     contact layer 303, and an electrode corresponding to
     the electrode 62 is formed on the $SiO_2$ film 304 so as
     to fill the foregoing recess.  It should be noted that
     the $SiO_2$ film 304 is formed to have a thickness of
35   about 200 nm by a high-temperature CVD process, and
     the foregoing opening is formed in the $SiO_2$ film 304
     by a wet etching process using HF.

1      As explained already, the laser diode 400 of
the present embodiment minimizes the formation of
particles on the mask 301A and the yield of production
of the laser diode is improved substantially.  As the
5    laser diode 400 of FIG.13 allows the electrode 62 to
have a large area and a substantially flat top
surface, mounting process of the laser diode 400 is
facilitated substantially.

10   [FIFTH EMBODIMENT]
      As explained already, the selective growth
process used in the fabrication process of the laser
diode 300, 310 or 400 tends to cause the problem of
deposition of particles on the insulation mask.  This
15   problem of particle formation becomes particularly
serious in the process of forming the cladding layer
302 of AlGaN.  It should be noted that the AlN
component included in the AlGaN cladding layer 301 has
a tendency of preferential deposition on an $SiO_2$ film
20   that forms the mask 301, while the AlN component thus
deposited tend to act as a nucleus for formation of
the AlGaN cladding layer 301.
      In the experimental investigation that
constitutes the basis of the present invention, the
25   inventor of the present invention has discovered that
the formation of particles on an $SiO_2$ mask is
effectively suppressed in the selective growth process
of AlGaN conducted by an MOVPE process, by supplying
the gaseous source of the elements together with a gas
30   containing halogen.
      FIGS.14A - 14F explain the foregoing
experiments conducted by the inventor of the present
invention.
      Referring to FIG.14A, a 6H-SiC substrate 501
35   is cleaned in an organic solvent and then in water,
and the substrate 501 thus processed is then immersed
in a bath of HF for about 1 minute.

1    The substrate 501 thus processed is then
introduced into a reaction chamber of an MOVPE
apparatus so as to expose a (0001)Si surface thereof
on which the deposition of epitaxial layers is to be
5    made.  After evacuating the reaction chamber, the
native oxide film is removed from the surface of the
SiC substrate 501 by processing the substrate 501 at
1080°C in a hydrogen atmosphere for about 5 minutes.
Next, the substrate temperature is reduced to about
10   1050°C, and an AlGaN film 502 is grown on the
foregoing (0001)Si surface of the substrate 501 while
supplying TMG, TMA and $NH_3$ with respective flow rates
of 44 μmol/min, 8 μmol/min and 0.1 μmol/min, together
with a carrier gas of $H_2$.  The foregoing source gases
15   are applied directly to the substrate surface and the
AlGaN film 502 is grown thereon with a thickness of
about 1 μm.
    Next, in the step of FIG.14B, the supply of
TMG and TMA is interrupted and the substrate
20   temperature is lowered to 600°C or lower while
continuously directing the $NH_3$ gas to the substrate.
Thereby, the atmosphere inside the reaction chamber is
changed to $N_2$.  After cooling further to the room
temperature, the substrate 501 is taken out from the
25   deposition chamber, and an $SiO_2$ film 503 is formed on
the foregoing AlGaN film 502 with a thickness of 0.2
μm.
    Next, in the step of FIG.14C, a resist film
is formed on the $SiO_2$ film 503, followed by a
30   patterning process to from a resist pattern 504 having
a width of 2 μm, such that the resist pattern 504 is
repeated with a pitch of 30 μm.
    Next, in the step of FIG.14D, the $SiO_2$ film
is subjected to a wet etching process using HF as an
35   etchant to form a line and space pattern exposing the
AlGaN film 502.  After removing the resist pattern 504
by using an organic solvent, the substrate 501 is

1     returned to the reaction chamber of the MOVPE

apparatus. The reaction chamber is then evacuated,

and the native oxide film is removed from the exposed

part of the AlGaN film 502 by applying a heat

5     treatment process at 1050°C in $H_2$ atmosphere, while

supplying $NH_3$. Further, a selective epitaxial growth

of an AlGaN film 505 is made on the exposed surface of

the AlGaN film 502 by supplying TMG, TMA, $CH_3Cl$ and

$NH_3$ with respective flow rates of 44 μmol/min, 8

10     μmol/min, 52 μmol/min and 0.1 μmol/min, together with

a carrier gas of $H_2$.

    In the step of FIG.14F, the substrate

temperature is then lowered to below 600°C while

supplying $NH_3$ to the reaction chamber, such that the

15     atmosphere inside the reaction chamber is changed to

the $N_2$ atmosphere. Thereafter, the substrate

temperature is lowered to the room temperature.

    According to the selective growth process of

the present embodiment, the $CH_3Cl$ molecules supplied

20     in the step of FIG.14F to the reaction chamber

together with the gaseous source material release Cl

atoms as a result of the pyro-decomposition process

thereof, wherein the Cl atoms thus released suppresses

the AlN formation on the exposed surface of the AlGaN

25     film 502 by preferentially reacting with Al. The

supply of $CH_3Cl$ is preferably made to the reaction

chamber by a gas inlet different from the inlet used

for introducing a gaseous source of group V element

such as $NH_3$. Thereby, the nuclei formation on the

30     $SiO_2$ mask 503 is impeded and the deposition of

polycrystalline or particulate precipitates on the

mask 503 is suppressed.

    It should be noted that the element that

suppresses the AlN formation on the $SiO_2$ mask is by no

35     means limited to Cl but other halogen element such as

F can be used also for the same purpose. Further, the

compound that is used as the carrier of the halogen

1     atom is by no means limited to $CH_3Cl$ but other halogen
compounds, including a metal-organic compound
containing halogen, may also be used.

It should be noted that the selective
5     epitaxial growth process according to the present
embodiment is applicable not only to the fabrication
process of a ridge-type laser diode as described but
the present embodiment is also applicable to general
fabrication process of a semiconductor device that
10     includes a selective growth of a nitride film of a
group III element including Al.


[SIXTH EMBODIMENT]

In the GaN-family laser diodes 100, 200,
15     300, 310 and 400 described heretofore, it should be
noted that there is formed an electron blocking layer
51 of AlN formed adjacent to the active layer
structure 40, wherein the electron blocking layer 51
is doped with Mg to a high concentration level and
20     blocks the electrons that are injected into the active
layer structure 40 and subsequently causing an
overflow from the active layer structure 40 as a
result of the large electric field formed in the p-
type epitaxial structure 50. For this purpose, the
25     electron blocking layer 51 is generally formed to have
a composition that provides a large bandgap. Thus,
the optical waveguide layer 52 of p-type GaN or the
cladding layer 53 of p-type AlGaN is formed above the
electron blocking layer 51. It should be noted that
30     the p-type AlGaN cladding layer 53 has a relatively
large resistivity, and because of this, the foregoing
large electric is created.

FIG.15 shows the Mg concentration profile
used in the GaN-family laser diode disclosed in the
35     Japanese Laid-Open Patent Publication 10-56236 for the
part located above the active layer structure. It
should be noted that the GaN-family laser diode of

1  FIG.15 is formed on a sapphire substrate.

   Referring to FIG.15, the laser diode
includes, in addition to the foregoing electron
blocking layer, an optical waveguide layer of GaN

5  formed thereon as a part of the SCH structure and a
cladding layer of AlGaN, wherein the electron blocking
layer, the optical waveguide layer and the cladding
layer are all doped with Mg to the concentration level
of about $5 \times 10^{19} cm^{-3}$. Only the uppermost contact

10  layer of GaN is doped by Mg to the concentration level
of about $1 \times 10^{20} cm^{-3}$. It should be noted that the
laser diode 100 of the previous embodiment also uses
the Mg profile of FIG.15.

   On the other hand, the Mg concentration

15  profile of FIG.15 cannot avoid cracking in the
epitaxial layers used in nitride laser diodes. Such
cracks formed in the epitaxial layers provides
undesirable effect of decreased efficiency of laser
oscillation and increased threshold voltage. Thus, it

20  is desirable to reduce the crack formation as much as
possible.

   In the experimental investigation on the
laser diode 100 described previously, the inventor of
the present invention has discovered that the cracks

25  formed in the epitaxial layers of the laser diode is
reduced substantially when the Mg concentration level
is reduced in the p-type GaN optical waveguide layer
52 and the p-type AlGaN cladding layer 53, all located
above the active layer structure 40.

30   Referring to FIG.16, it can be seen that the
crack density observed on the surface of the cladding
layer 53 is reduced sharply when the Mg concentration
level in the GaN optical waveguide layer 52 and the
AlGaN cladding layer 53 is reduced below the

35  conventionally used value of $5 \times 10^{19} cm^{-3}$. When the
Mg concentration level is reduced below about $4 \times 10^{19} cm^{6-3}$, particularly below than about $3 \times 10^{19} cm^{-3}$,

1     it can be seen that the observed crack density becomes
      substantially zero.  In FIG.16, it should be noted
      that the vertical axis represents the crack density
      while the horizontal axis represents the Mg
5     concentration level.

            In conformity with the crack density, the
      resistance of the laser diode 100 is reduced sharply
      when the Mg concentration level in the optical
      waveguide layer 52 and the cladding layer 53 is
10    reduced.  Thereby, a minimum resistance is reached
      when the optical waveguide layer  52 and the cladding
      layer 53 have the Mg concentration level of 3 - 4 x
      $10^{19} cm^{-3}$ as represented in FIG.17, wherein FIG.17
      shows the Mg concentration level in the horizontal
15    axis and the drive voltage necessary for flowing a
      drive current of 100 mA in the vertical axis.  With
      further decrease in the Mg content, it can be seen
      that the resistance of the laser diode 100 starts to
      increase again, while this effect is merely attributed
20    to the depletion of carries in the optical waveguide
      layer 52 and in the cladding layer 53 due to the
      excessively reduced concentration level of Mg.

            FIG.18 shows the doping profile of Mg for
      the laser diode 100 of FIGS.6A and 6B optimized in
25    view of the discovery of the relationship of FIG.17.

            Referring to FIG.18, the electron blocking
      layer 51 of p-type AlGaN has a composition of
      $Al_{0.18}Ga_{0.82}N$ and is formed on the active layer
      structure 40 with a thickness of about 20 nm, wherein
30    the electron blocking layer 51 is doped with Mg to the
      concentration level of about 1 x $10^{20} cm^{-3}$.  On the
      electron blocking layer 51, the optical waveguide
      layer 52 of p-type GaN is formed with a thickness of
      about 100 nm, wherein the optical waveguide layer 52
35    is doped with Mg to the concentration level of about 4
      x $10^{19} cm^{-3}$.  Further, the cladding layer 53 of p-type
      AlGaN has a composition of $Al_{0.09}GA_{0.91}N$ as noted

1      before wherein the cladding layer 53 is formed on the optical waveguide layer 52 with a thickness of about 550 nm. The cladding layer 53 is also doped with Mg to the concentration level of about $4 \times 10^{19} cm^{-3}$.

5      On the cladding layer 53, the contact layer 54 of p-type GaN is formed with a thickness of about 80 nm, wherein the contact layer 53 is doped with Mg to the concentration level of about $1.5 \times 10^{20} cm^{-3}$.

According to the present invention, the

10      crack density in the optical waveguide layer 52 and the cladding layer 53 is minimized by setting the Mg concentration level in the layers 52 and 53 to be about $4 \times 10^{19} cm^{-3}$ or less. Thereby, the resistance of the laser diode is minimized. Further, the

15.     threshold voltage of the laser diode is decreased by increasing the Mg concentration level in the electron blocking layer 51 above the foregoing value of about $4 \times 10^{19} cm^{-3}$. Further, the increase of the laser diode resistance as a result of the excessively low impurity

20      concentration level is also avoided.

FIG.19 shows a modification of the embodiment of FIG.18 in which the Mg concentration level in the optical waveguide layer 52 and the cladding layer 53 is decreased to about $3 \times 10^{19} cm^{-3}$

25      in view of the relationship of FIG.17. In the case of FIG.19, too, the crack density in the epitaxial layers constituting the laser diode 100 is reduced to substantially zero by combining the electron blocking layer 51 and the contact layer 54, which are doped to

30      a high concentration level. Thereby, the crack density, and hence the resistance, in the epitaxial layers is successfully minimized.

Further, the present invention is not limited to the embodiments described heretofore, but

35      various variations and modifications may be made without departing from the scope of the invention.

The present application is based on Japanese

1  priority applications No.10-135425 and 10-353241 filed
   respectively on May 18, 1998 and December 11, 9998,
   the entire contents of which are hereby incorporated
   by reference.

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1    <u>WHAT IS CLAIMED IS</u>

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     1. An optical semiconductor device,
comprising:

     a substrate of SiC having a first
conductivity type;

10      a buffer layer of AlGaN formed on said
substrate epitaxially, said buffer layer having said
first conductivity type and a composition represented
by a compositional parameter x as $Al_xGa_{1-x}N$;

     a first cladding layer having said first

15 conductivity type, said first cladding layer being
formed on said buffer layer epitaxially;

     an active layer formed epitaxially on said
first cladding layer;

     a second cladding layer having a second,

20 opposite conductivity type, said second cladding layer
being formed on said active layer epitaxially;

     a first electrode provided so as to inject
first-type carriers having a first polarity into said
second cladding layer; and

25      a second electrode provided on said
substrate so as to inject second-type carriers having
a second polarity,

     said buffer layer containing said first type
carriers with a concentration level in the range from

30  $3 \times 10^{18} cm^{-3}$ to $1 \times 10^{20} cm^{-3}$ and said compositional
parameter x larger than 0 but smaller than 0.4 (0 < x
<0.4).

35

     2. An optical semiconductor device as

1    claimed in claim 1, wherein said substrate contains
carriers of said first conductivity type with a
concentration level in the range from 1 x $10^{18}$ - 1 x
$10^{20} cm^{-3}$.

5

3.  An optical semiconductor device as
10   claimed in claim 1, wherein said compositional
parameter x of said buffer layer is less than 0.09 (x
< 0.09).

15

4.  An optical semiconductor device as
claimed in claim 1, wherein said substrate has a
(0001)Si surface of SiC and wherein said buffer layer
20   is formed on said (0001)Si surface in intimate contact
with said substrate.

25

5.  A method of fabricating an optical
semiconductor device, comprising the step of: growing
an AlGaN film having a composition of $Al_xGa_{1-x}N$ (0 < x
< 0.4) on an SiC substrate by a metal-organic vapor
30   phase epitaxy process, under a pressure of about 90
Torr or less.

35

6.  An optical semiconductor device,
comprising:

1       a substrate of SiC having a first
conductivity type;

       a buffer layer of AlGaN formed on said
substrate epitaxially;

5       a first cladding layer of AlGaN having said
first conductivity type, said first cladding layer
being formed on said buffer layer epitaxially;

       an optical waveguide layer of GaN having
said first conductivity type, said optical waveguide
10     layer being formed on said first cladding layer
epitaxially;

       an active layer formed epitaxially on said
optical waveguide layer, said active layer containing
Ga as a group III element and N as a group V element;

15     a second cladding layer of AlGaN having a
second, opposite conductivity type, said second
cladding layer being formed on said active layer
epitaxially;

       a first electrode provided so as to inject
20     first-type carriers having a first polarity into said
second cladding layer; and

       a second electrode provided on said
substrate so as to inject second-type carriers having
a second polarity,

25     said substrate having a top surface
separated from a bottom surface of said active layer
by a distance of about 1.6 μm or more.

30

       7. An optical semiconductor device as
claimed in claim 6, wherein said buffer layer has a
composition represented by a compositional parameter x
35     as $Al_xGa_{1-x}N$, said first cladding layer has a
composition represented by a compositional parameter y
as $Al_yGa_{1-y}N$, and said second cladding layer has a

1    composition represented by a compositional parameter z
as $Al_zGa_{1-z}N$, said compositional parameter x having a
value equal to or larger than 0.08 but smaller than
0.5 ($0.08 \leq x < 0.5$), said compositional parameter y
5    having a value equal to or larger than 0.05 but equal
to or smaller than said compositional parameter x
($0.05 \leq y \leq x$), said compositional parameter z having
a value smaller than said compositional parameter y ($z
< y$).

10

8.    An optical semiconductor device,
15    comprising:
a substrate of SiC having a first
conductivity type;
a first cladding layer having a first
conductivity type, said first cladding layer being
20    formed on said substrate epitaxially;
an active layer formed epitaxially on said
first cladding layer;
a second cladding layer having a second,
opposite conductivity type, said second cladding layer
25    being formed on said active layer epitaxially;
a third cladding layer having said second
conductivity type, said third cladding layer being
formed on said second cladding layer epitaxially;
a first electrode provided so as to inject
30    first-type carriers having a first polarity into said
second cladding layer; and
a second electrode provided on said
substrate so as to inject second-type carriers having
a second polarity,
35    said third cladding layer having a ridge
structure,
wherein an insulating film is interposed

1    between said second cladding layer and said third
cladding layer, said insulating film having an opening
in correspondence to said ridge structure, with a
width smaller than a width of said ridge structure.

5

      9.  An optical semiconductor device as
10   claimed in claim 8, wherein said contact layer covers
a top surface and both side walls of said ridge
structure continuously.

15

      10.  An optical semiconductor device as
claimed in claim 9, wherein said first electrode
covers a top surface and both side walls of said
20   contact layer, corresponding respectively to said top
surface and both side walls of said ridge structure,
continuously.

25

      11.  An optical semiconductor device as
claimed in claim 10, wherein said ridge structure is
formed in a recess structure exposing said insulation
30   film, and wherein said first electrode fills said
recess structure.

35

      12.  An optical semiconductor device as
claimed in claim 10 wherein said third cladding layer

1    is formed of a nitride of a group III element.

5

13.    An optical semiconductor device,
comprising:
        a substrate of SiC having a first
conductivity type;
10       a first cladding layer having a first
conductivity type, said first cladding layer being
formed on said substrate epitaxially;
        an active layer formed epitaxially on said
first cladding layer;
15       a second cladding layer having a second,
opposite conductivity type, said second cladding layer
being formed on said active layer epitaxially;
        a third cladding layer having said second
conductivity type, said third cladding layer being
20   formed on said second cladding layer epitaxially;
        a contact layer of said second conductivity
type, said contact layer being formed on said third
cladding layer;
        a first electrode provided on said contact
25   layer;
        a second electrode provided on said
substrate;
        said third cladding layer forming a ridge
structure having a T-shaped cross-section,
30       said third cladding layer including, at a
bottom part thereof, a pair of cuts, such that said
cuts penetrate from respective lateral sides of said
ridge structure toward a center of said ridge
structure.

35

1       14. A method of fabricating a semiconductor device, comprising the steps of:

forming an insulation pattern on a semiconductor layer such that said insulation pattern has an opening; and

5       forming, on said insulation pattern, a regrowth region of a nitride of Al and a group III element in correspondence to said opening,

said step of forming the regrowth region

10    being conducted by an metal-organic vapor phase epitaxy process.

15

15. A method as claimed in claim 14, wherein said step of forming said regrowth region includes the step of admixing a halogen to a source material used in said metal-organic vapor phase

20    epitaxy process for forming said nitride.

25       16. A method as claimed in claim 15, wherein said step of forming said regrowth region includes the step of supplying said halogen to a reaction chamber of a metal-organic vapor phase deposition apparatus, in which said metal-organic

30    vapor phase epitaxy process occurs, separately to a gaseous source of nitrogen.

35

17. A method as claimed in claim 14, wherein said step of forming said regrowth region is

1     conducted by using a metal organic compound containing
halogen.

5

     18.  An optical semiconductor device,
comprising;

     a substrate;

10     a first cladding layer of a nitride of a
group III element formed epitaxially on said
substrate, said first cladding layer having an n-type
conductivity;

     a first optical waveguide layer of a nitride

15     of a group III element formed epitaxially on said
first cladding layer, said first optical waveguide
layer having an n-type conductivity;

     an active layer of a nitride of a group III
element formed epitaxially on said first optical

20     waveguide layer;

     an electron blocking layer of a nitride of a
group III element formed epitaxially on said active
layer, said electron blocking layer having a p-type
conductivity;

25     a second optical waveguide layer of a
nitride of a group III element formed epitaxially on
said electron blocking layer, said second optical
waveguide layer having a p-type conductivity;

     a second cladding layer of a nitride of a

30     group III element formed epitaxially on said second
optical waveguide layer, said second cladding layer
having a p-type conductivity;

     a contact layer of a nitride of a group III
element formed epitaxially on said second cladding

35     layer, said contact layer having a p-type
conductivity;

     a first electrode provided on said contact

1    layer; and

        a second electrode provided on said
substrate;

        each of said electron blocking layer, said

5    second optical waveguide layer and said second
cladding layer being doped by Mg;

        wherein said second optical waveguide layer
and said second cladding layer contain Mg therein with
a concentration level lower than a concentration level

10    of Mg in any of said electron blocking layer and said
contact layer.

15

        19.  An optical semiconductor device as
claimed in claim 18, wherein said second optical
waveguide layer and said second cladding layer contain
Mg with a concentration level not exceeding 4 x

20    $10^{19} cm^{-3}$.

25        20.  An optical semiconductor device as
claimed in claim 19, wherein said electron blocking
layer and said contact layer contain Mg with a
concentration level exceeding 4 x $10^{19} cm^{-3}$.

30

        21.  A semiconductor wafer, comprising:
        an SiC substrate having an n-type

35    conductivity; and
        an AlGaN layer having an n-type conductivity
formed on said SiC substrate with a composition

1  represented as $Al_xGa_{1-x}N$,

   wherein said AlGaN layer has a carrier
density in the range between $3 \times 10^{18} - 1 \times 10^{20} cm^{-3}$,
and

5  wherein said compositional parameter x is
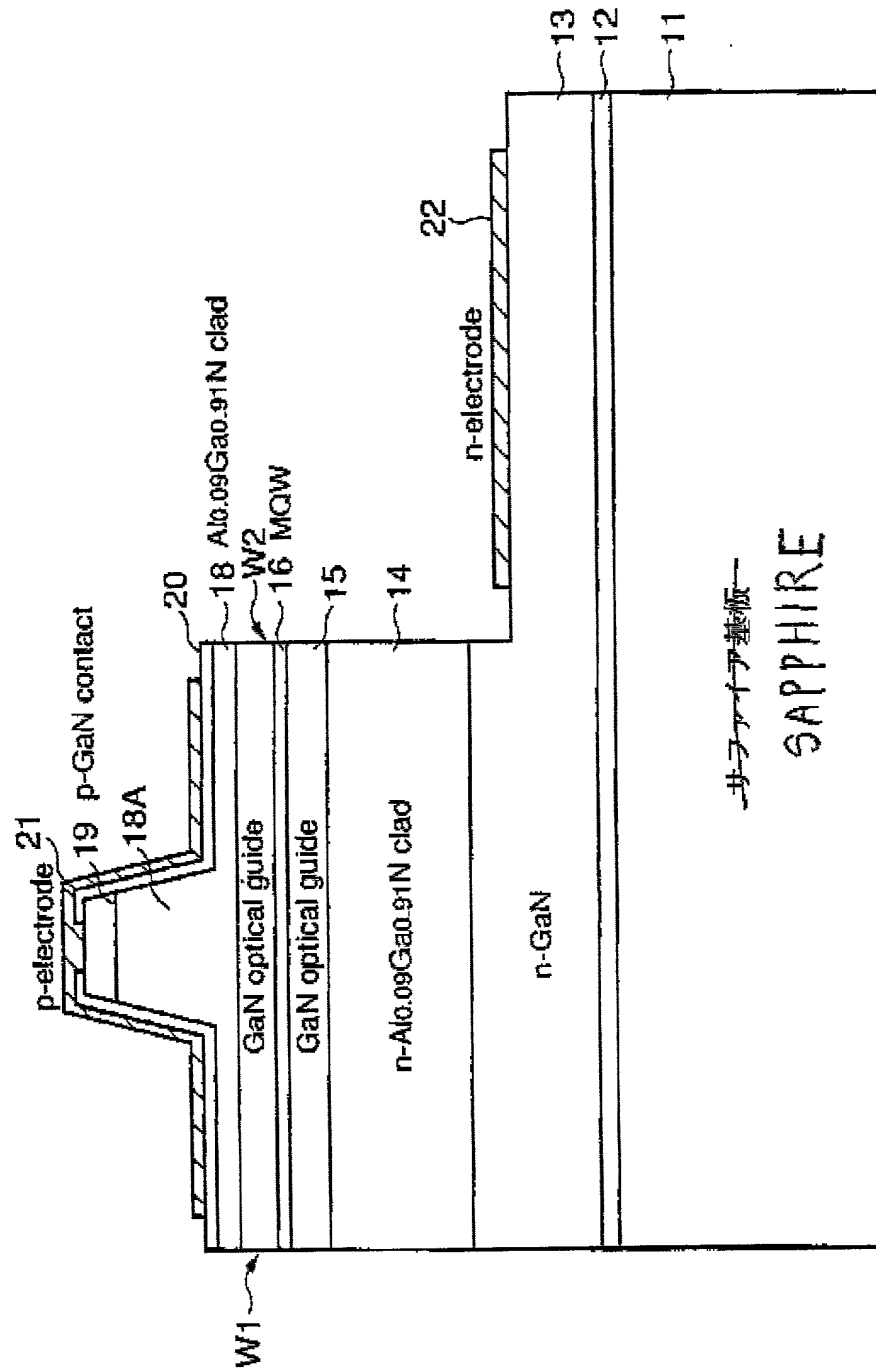larger than 0 but smaller than 0.4 (0 < x < 0.4).

10

   22. A semiconductor wafer as claimed in
claim 21, wherein said substrate contains carriers of
said first conductivity type with a concentration
15  level in the range from $1 \times 10^{18} - 1 \times 10^{20} cm^{-3}$.

20  23. A semiconductor wafer as claimed in
claim 21, wherein said compositional parameter x of
said buffer layer is less than 0.09 (x < 0.09).

25

   24. An optical semiconductor device as
claimed in claim 21, wherein said substrate has a
(0001)Si surface of SiC and wherein said buffer layer
30  is formed on said (0001)Si surface in intimate contact
with said substrate.

35

1 ABSTRACT OF THE DISCLOSURE

An optical semiconductor device includes an SiC substrate having an n-type conductivity, and an AlGaN buffer layer having an n-type conductivity

5 formed on the SiC substrate with a composition represented as $Al_xGa_{1-x}N$, wherein the AlGaN buffer layer has a carrier density in the range between $3 \times 10^{18} - 1 \times 10^{20} cm^{-3}$, and the compositional parameter x is larger than 0 but smaller than 0.4 (0 < x < 0.4).

10

15

20

25

30

35

【書類名】　図面

【図1】

従来の青色レーザダイオードの構成を示す図



FIG 1
PRIOR ART

p-electrode 21
19 p-GaN contact
18A
20
18 Al0.09Ga0.91N clad
W2
16 MQW
15
14
22
n-electrode

GaN optical guide
GaN optical guide
n-Al0.09Ga0.91N clad
n-GaN
サファイア基板 SAPPHIRE

W1

13
12
11

【図２】

(A),(B)は、本発明の第1実施例の基礎となる実験で使われた試料、
および実験結果を示す図

FIG2A (A)

| | |
|---|---|
| | 6 |
| n-GaN:Si | 3 |
| n-AlGaN:Si | 2 |
| n-SiC:N | 1 |
| | 5 |

(B)

FIG2B



INTERFACE RESISTIVITY 界面抵抗率 (Ωcm²)

n-AlGaN層のキャリア濃度 (cm⁻³)
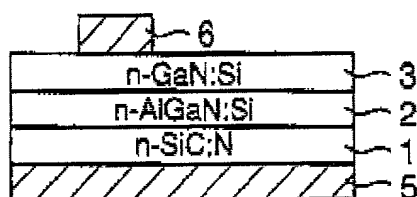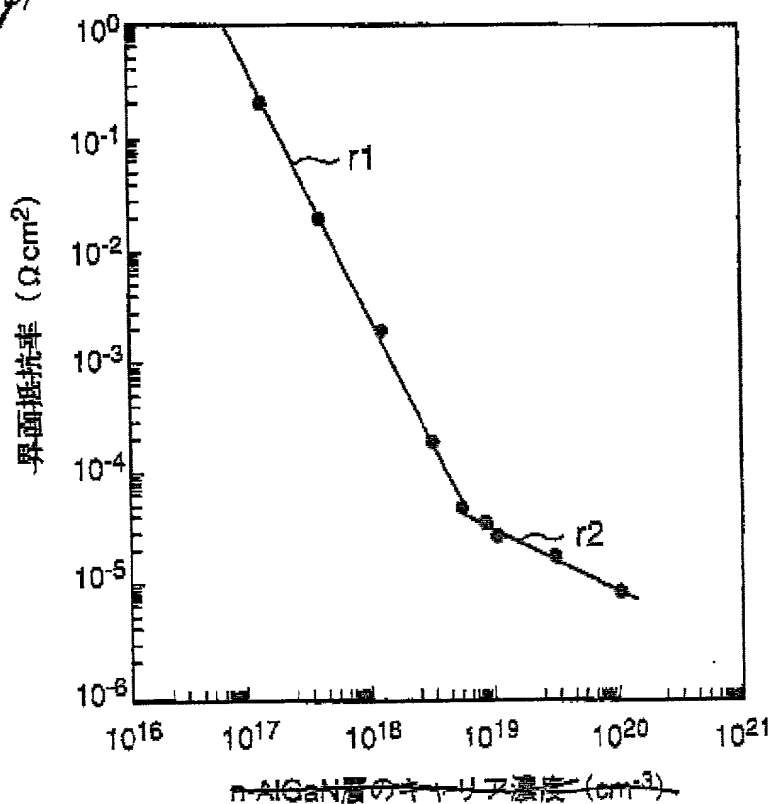
CARRIER DENSITY IN η-AlGaN (cm⁻3)

【図3】

# FIG 3

本発明第1実施例の基礎となる実験の別の結果を示す図



INTERFACE RESISTIVITY

界面抵抗率（Ω cm²）

r3

r4

n-SiC基板のキャリア濃度（cm⁻³）
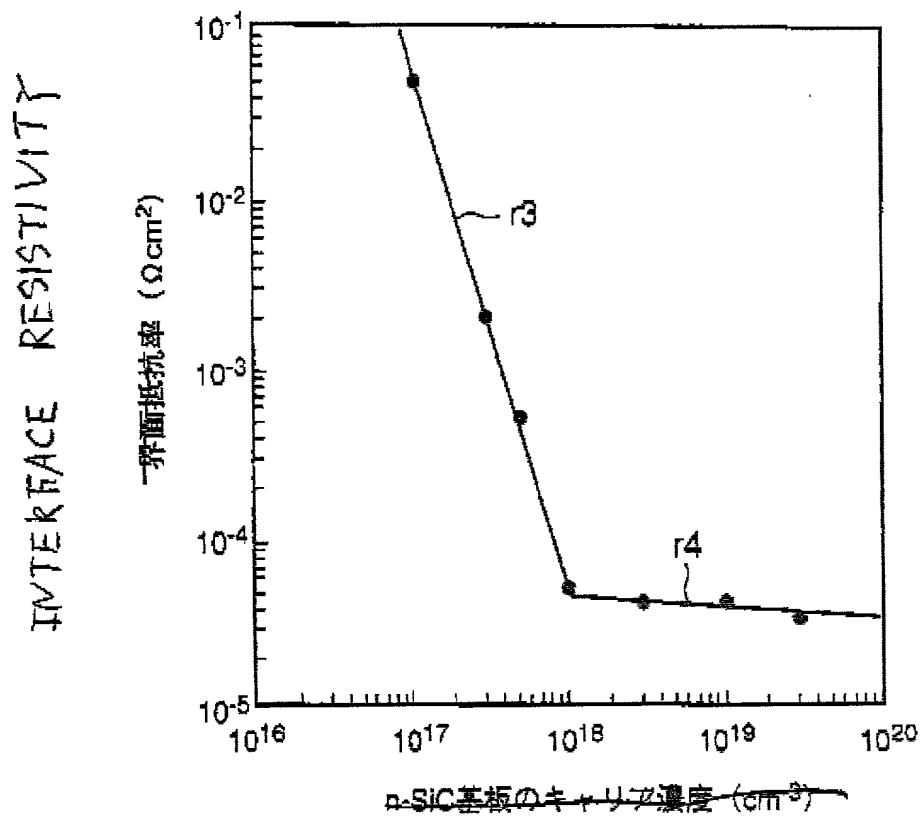
CARRIER DENSITY IN η-SiC SUBSTRAT (cm-3)

【図4】

FIG 4

本発明第1実施例の基礎となる実験の別の結果を示す図



INTERFACE RESISTIVITY

界面抵抗率 （Ωcm²）

Al組成 （%）

Al CONTENT

【図５】

FIG 5

本発明第1実施例の基礎となる実験の別の結果を示す図
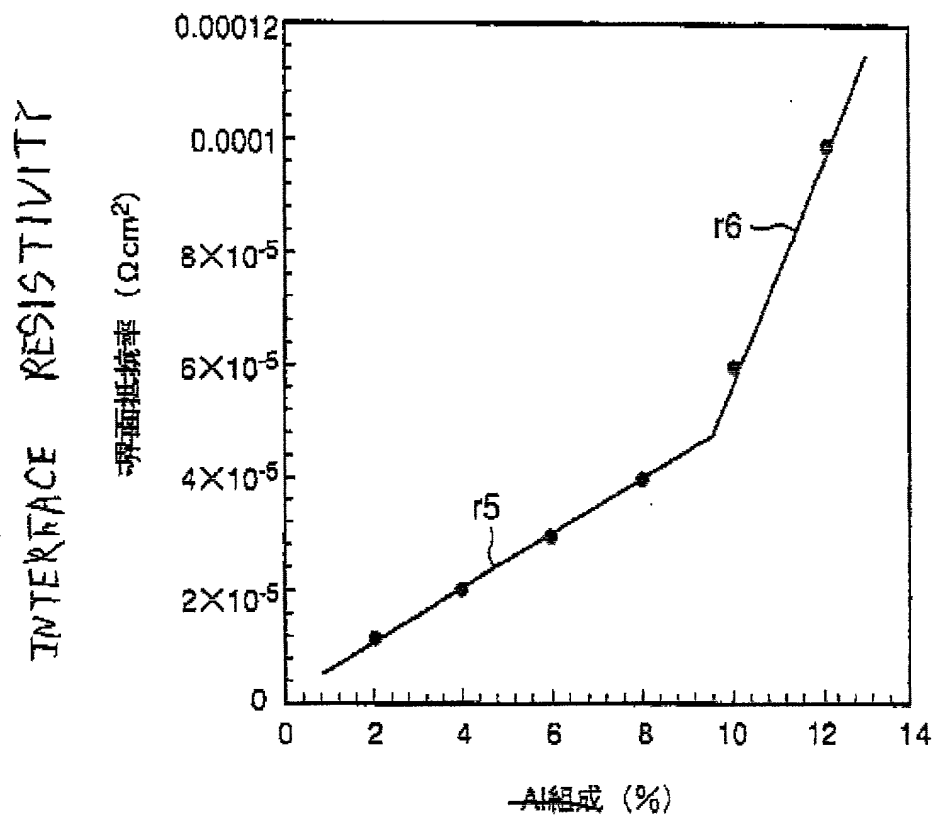


MINIMUM Al CONTENT FOR PLANAR SURFACE
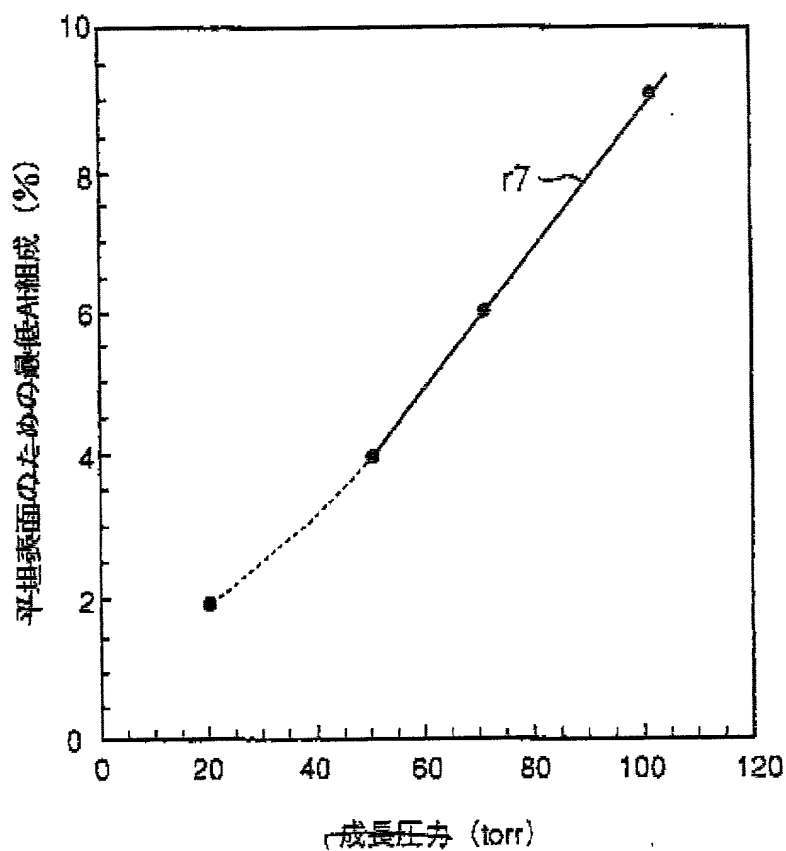
DEPOSITION PRESSURE

【図6】

(A),(B)は、本発明の第1実施例によるレーザダイオードの
構成を示す図

FIG6A

FIG6B

<1100>

HR

HR

100

In

p-GaN

p-Al0.09Ga0.91N

p-GaN

n-GaN

p-Al0.18Ga0.82N

n-Al0.09Ga0.91N

n-GaN

n-Al0.09Ga0.91N

n-SiCsubstrate

54

62
61
53
52
51
40
35

34

33

32

31

63

50

30
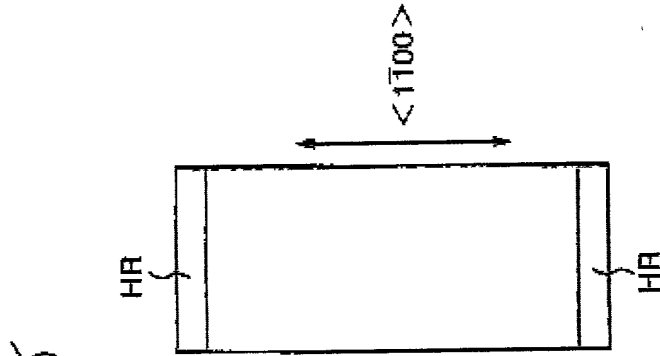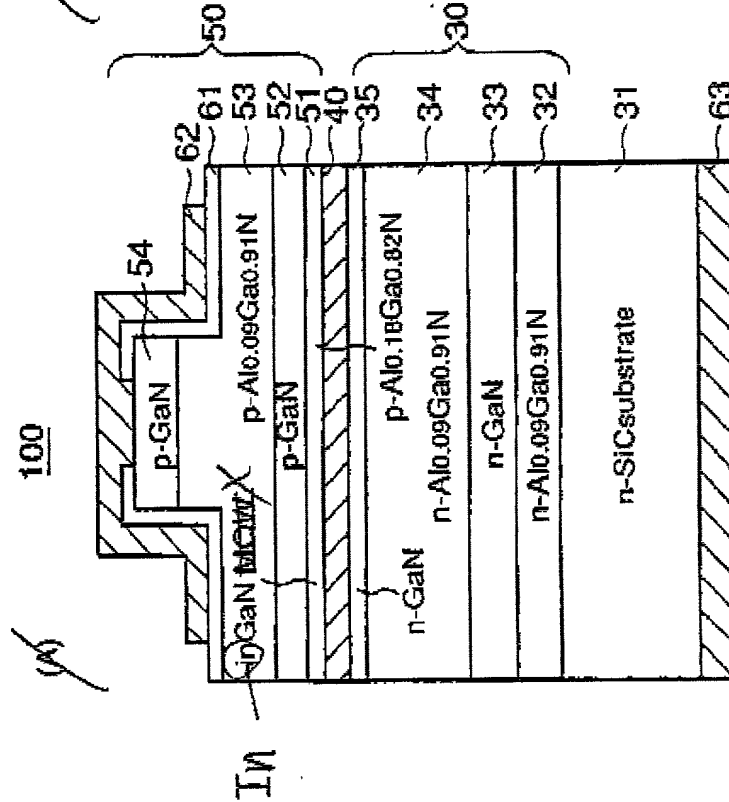
【図7】

# FIG 7

本発明の第2実施例の基礎となる実験の結果を示す図



LASER THRESHOLD CURRENT DENSITY

レーザのしきい値電流密度(KA/cm²)
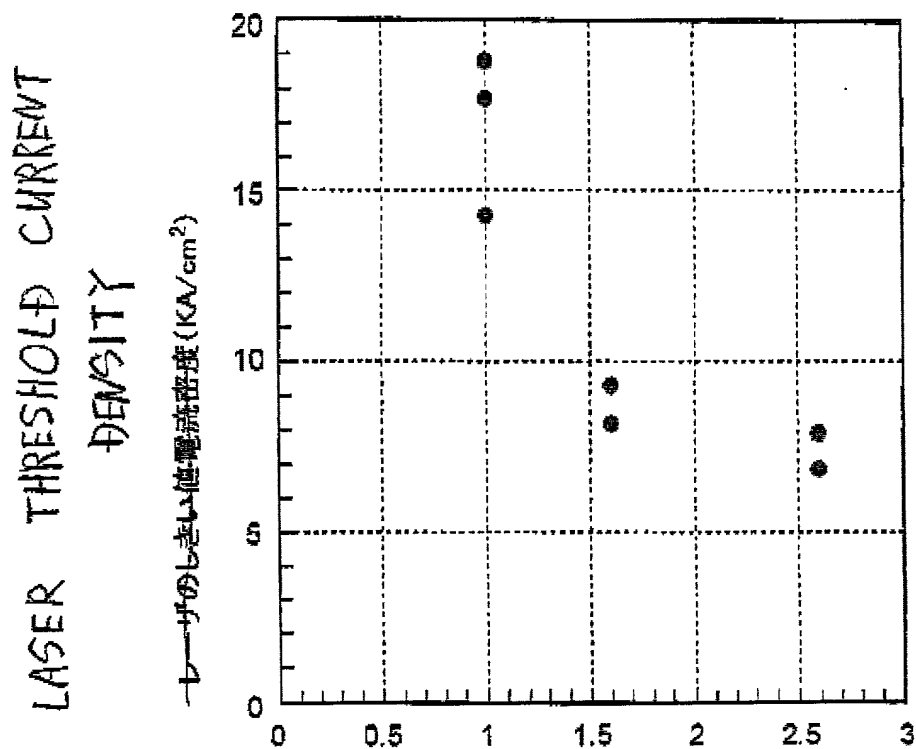
SiC基板と活性層の間に存在する層の膜厚の合計（μm）

TOTAL FILM THICKNESS BETWEEN SiC SUBSTRATE AND ACTIVE LAYER
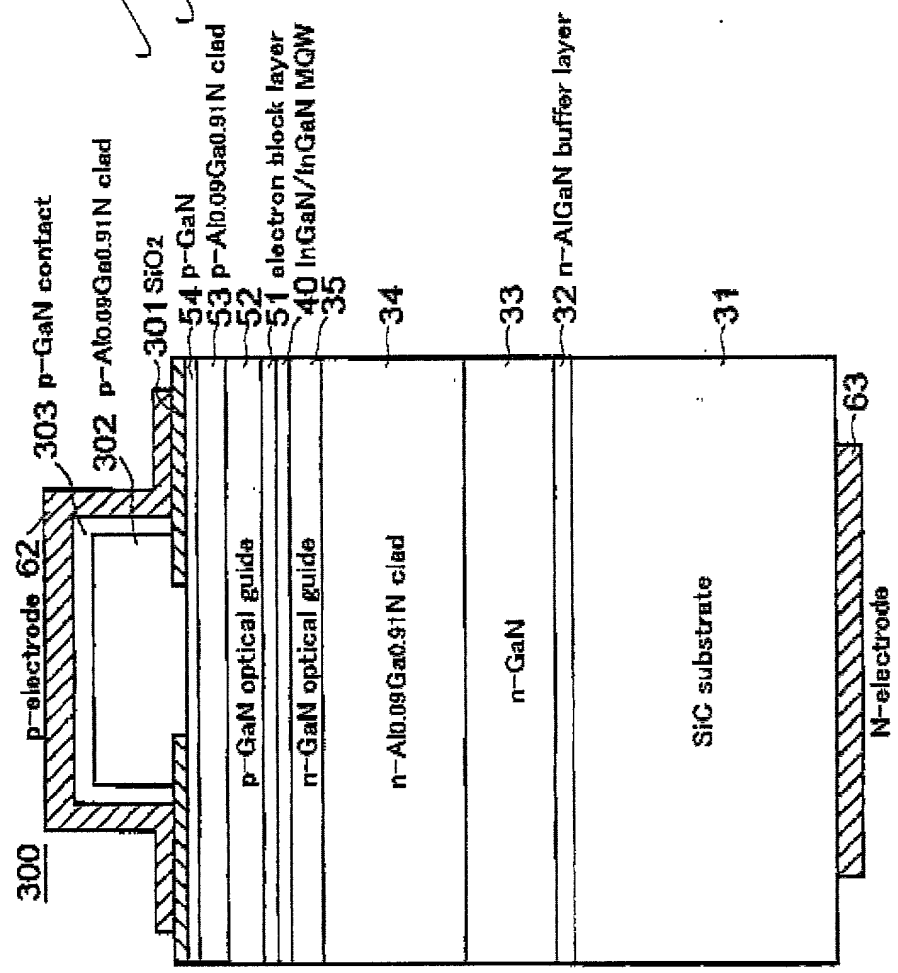
【図８】

本発明の第2実施例によるレーザダイオードの構造を示す図

FIG 8

electrode

electrode

200

62 p電極層(Ni/Ti/Au)

54 p-GaNコンタクト層(0.1μm)

61 SiO₂

53 p-Al0.08Ga0.92Nクラッド層(0.55μm)

52 p-GaN光ガイド層(0.1μm)

51 p-Al0.18Ga0.82N電流ブロック層(20nm)

40 In0.15Ga0.85N/In0.03Ga0.97N MQW活性層(4nm/5nm,3周期) 3 times

35 n-GaN光ガイド層(0.1μm)

34 n-Al0.10Ga0.90Nクラッド層(1.5μm)

32 n-Al0.15Ga0.85Nバッファ層(1.0μm)

31 n-SiC基板

63 n電極層(Ni/Ti/Au)

【図9】

図8のレーザダイオードの一変形例を示す図

FIG 9

electrode

electrode

210

62 p電極植(Ni/Ti/Au)

54 p-GaNコンタクト層(0.1μm)

61 SiO₂

53 p-Al0.08Ga0.92Nクラッド生層(0.55μm)

52 p-GaN光ガイド層(0.1μm)

51 p-Al0.18Ga0.82Nエレクトロニヒブロック生層(20nm)

40 In0.15Ga0.85N/In0.03Ga0.97N MQW活性生層(4nm/5nm,3周期) 3 times

35 N-GaN光ガイド層(0.1μm)

34 n-Al0.10Ga0.90Nクラッド層(1.15μm)

32 n-Al0.10Ga0.90Nバッファ層(0.35μm)

31 n-SiC基板

63 n電極(Ni/Ti/Au)

【図１０】

(A)は、本発明の第3実施例によるレーザダイオードの製造工
程を示す図（その１）

FIG 10 A

【図１１】

(B)は、本発明の第3実施例によるレーザダイオードの製造工程を示す図（その2）

FIG10B

p-electrode 62
303 p-GaN contact
302 p-Al0.09Ga0.91N clad
301 SiO2
54 p-GaN
53 p-Al0.09Ga0.91N clad
52 electron block layer
51 InGaN/InGaN MQW
40
35
34 n-Al0.09Ga0.91N clad
33 n-GaN
32 n-AlGaN buffer layer
31 SiC substrate

p-GaN optical guide
n-GaN optical guide

63 N-electrode

300

(B)

【図１２】

FIG 11

本発明第3実施例によるレーザダイオードの一変形例を示す図



310

p-electrode 62

303 p-GaN contact

301G air gap

302 p-Al0.09Ga0.91N clad

61 SiO2

54 p-GaN

53 p-Al0.09Ga0.91N clad

p-GaN optical guide 52

51electron block layer

n-GaN optical guide 40

InGaN/InGaN MQW

35

n-Al0.09Ga0.91N clad 34

n-GaN 33

32

n-AlGaN buffer layer

SiC substrate 31

63

N-electrode
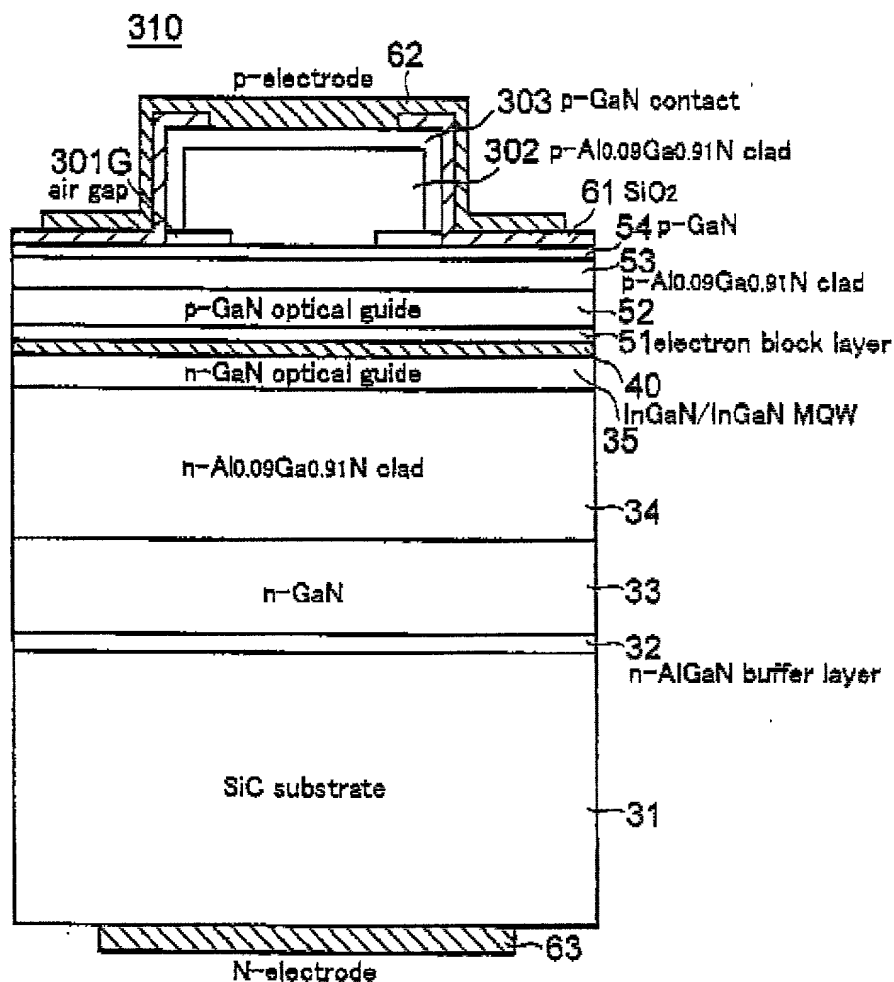
【図１３】

(A),(B)は、本発明第3実施例の選択成長工程で使われるマスク、
および本発明第4実施例の選択成長工程で使われるマスクを示
す図

width
SiO2幅:299μm
301 pitch
繰り返し周期:300μm

FIG12A (A)

width
開口部の幅:1μm
width
SiO2幅:6μm
301A pitch
繰り返し周期:300μm

301c

301a 301b

FIG12B (B)

301W

301n
広い開口部の幅:287μm
width
狭い開口部の幅:1μm
width
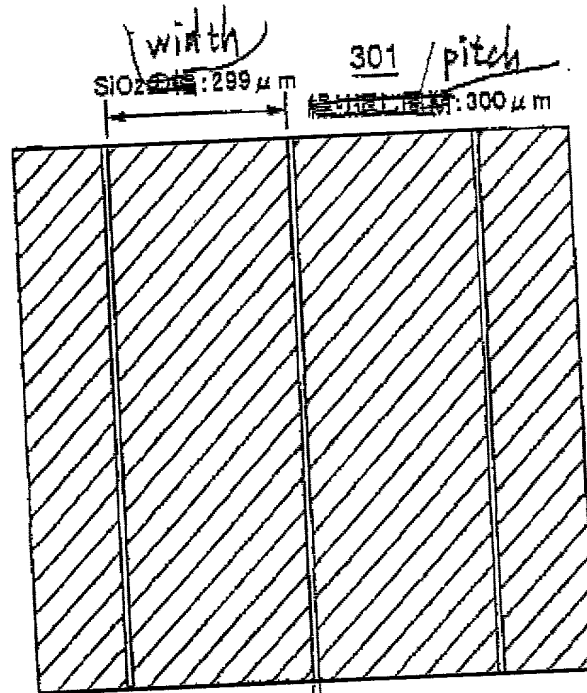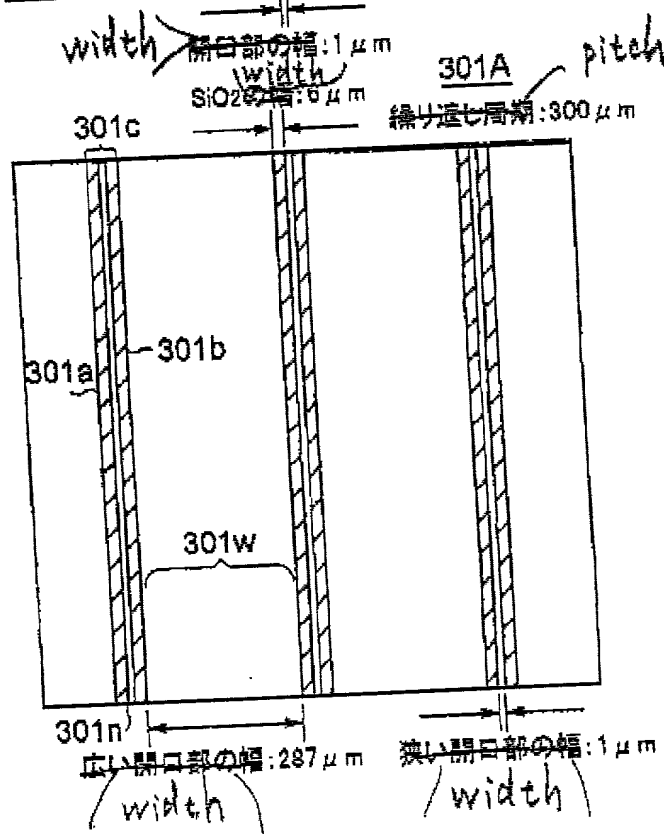
【図１４】

本発明の第4実施例によるレーザダイオードの構成を示す図

FIG.13

400

p-AlGaNクラッド 302
p-GaNコンタクト 303
第1 SiO2膜 301A
62 p電極座
303A
304 第2 SiO2膜
302A
54 p-GaNキャップ
53 p-AlGaNクラッド
52 p-GaN光ガイド
51 p-AlGaNエレクトロンコンファインメントブロック
40 InGaN MQW
35 n-GaN光ガイド
34 n-AlGaNクラッド
31 n-SiC基板
63 n電極
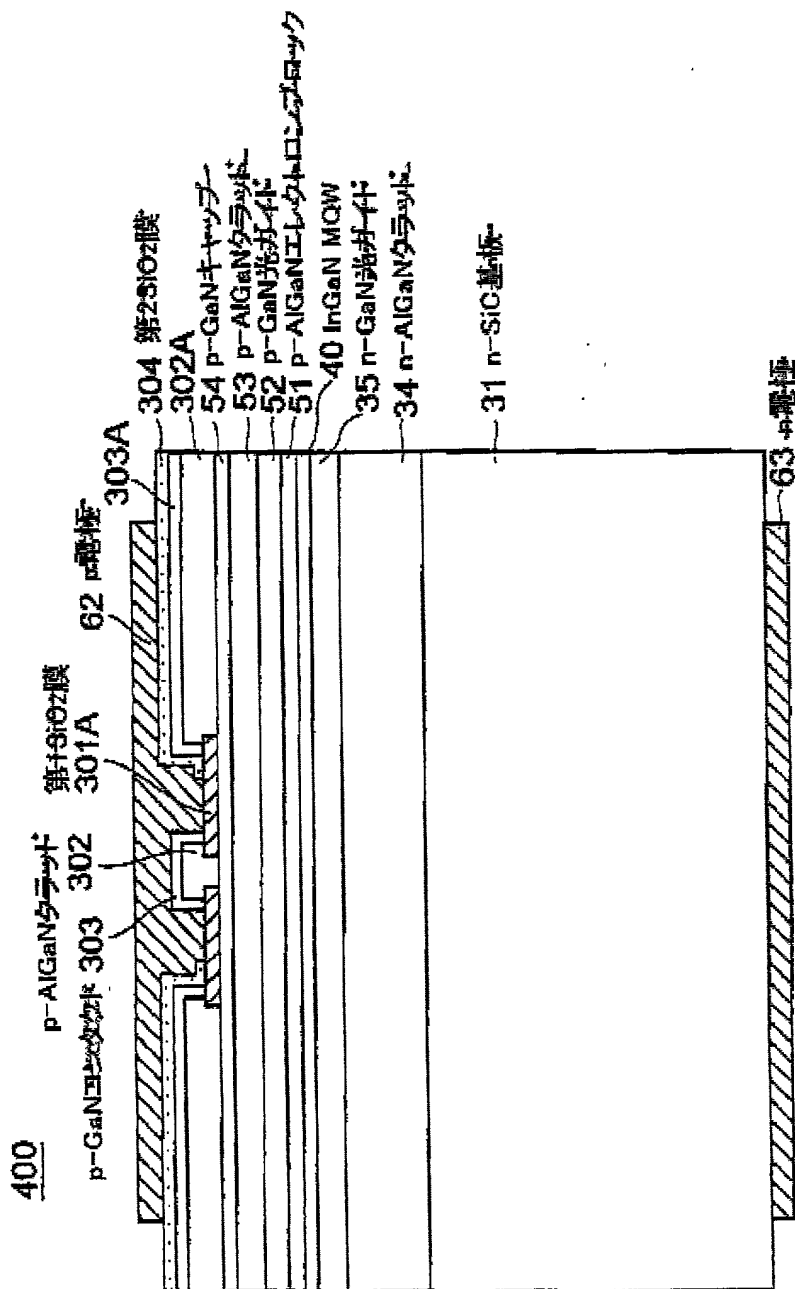
【図１５】

(A)〜(F)は、本発明の第5実施例による選択成長工程を示す図

FIG14A (A)
502 AlGaN
501 基板

FIG14B (B)
503 SiO2
502
501

FIG14C (C)
504 レジスト
503
502
501

FIG14D (D)
504
503
502
501

FIG14E (E)
503
502
501

FIG14F (F)
CH3Cl　TMG　NH3
TMG
AlGaN
505
503
502
501
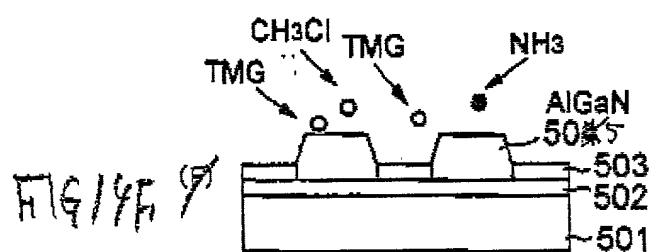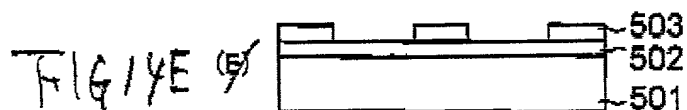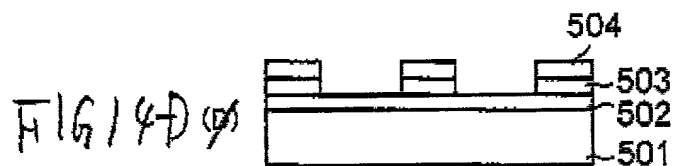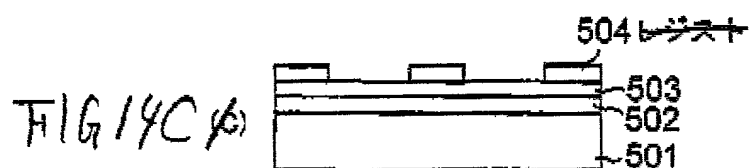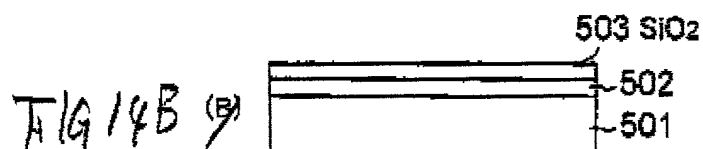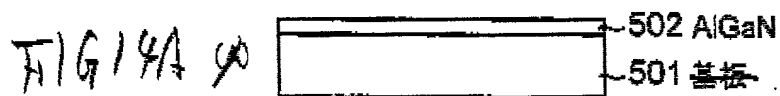
【図１６】

FIG15　PRIOR ART

従来の青色レーザダイオードにおけるp型エピタキシャル層中
の不純物分布を示す図



DISTANCE FROM ACTIVE LAYER
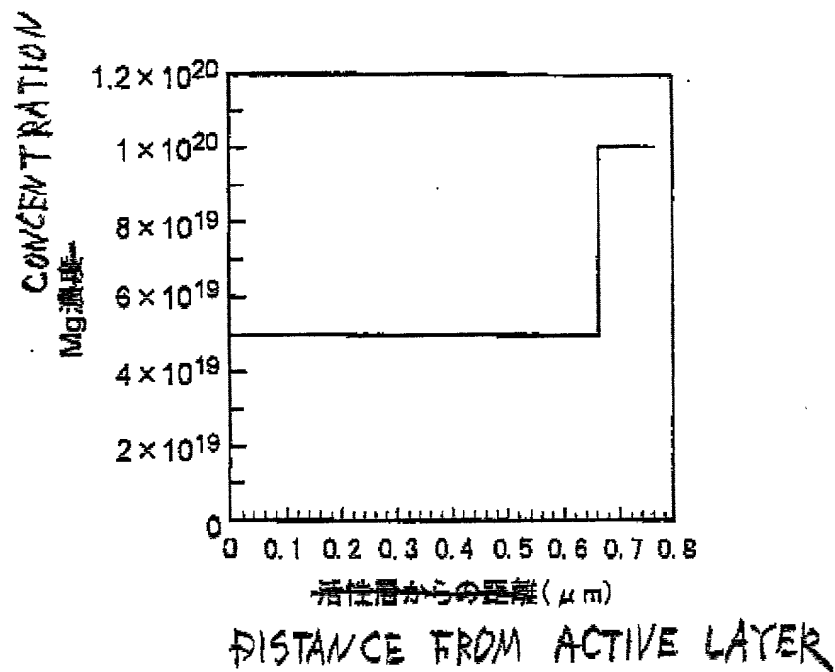
【図１７】

FIG 16

本発明の第6実施例の基礎となる実験結果を示す図



クラック密度とMg濃度

CRACK DENSITY
クラック密度(cm$^{-1}$)

Mg濃度(×10$^{19}$cm$^{-3}$)

CONCENTRATION
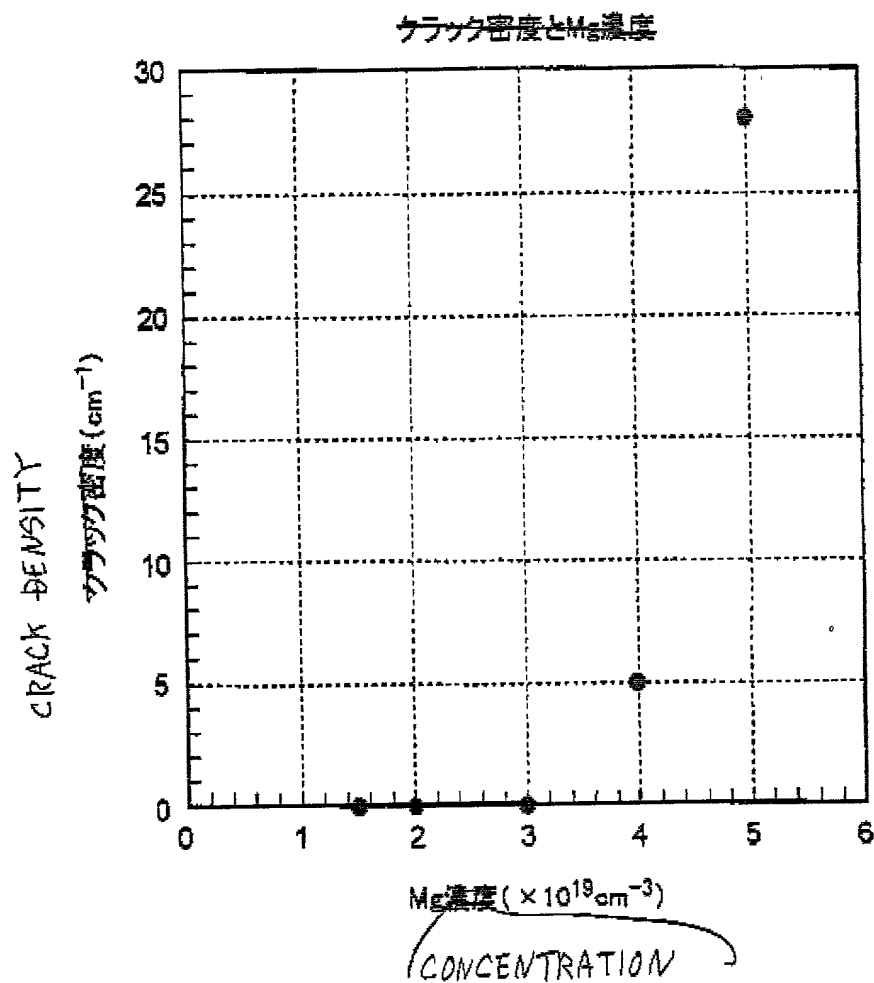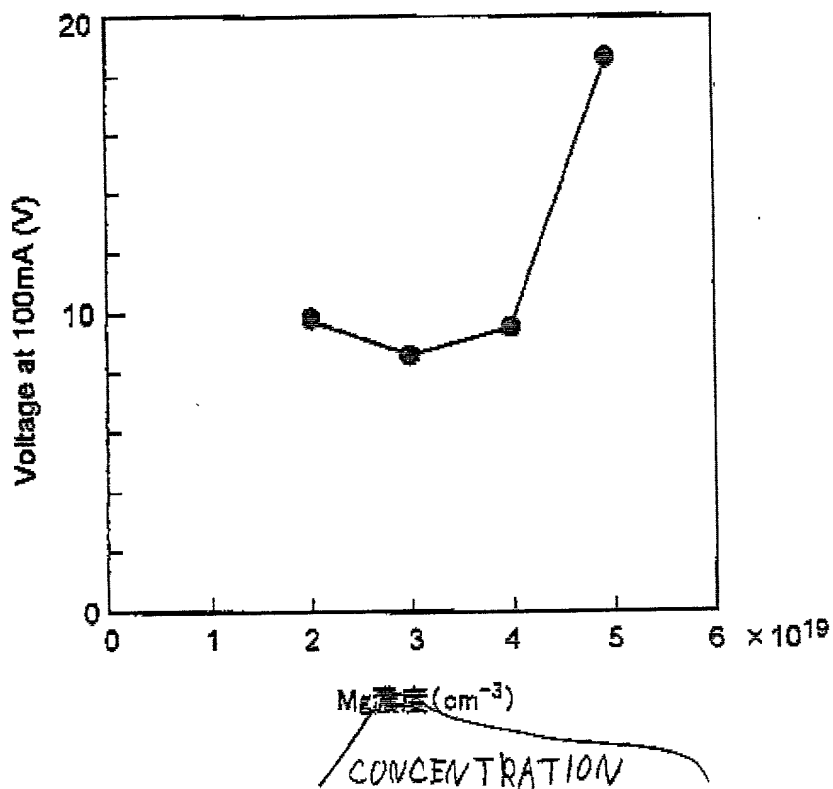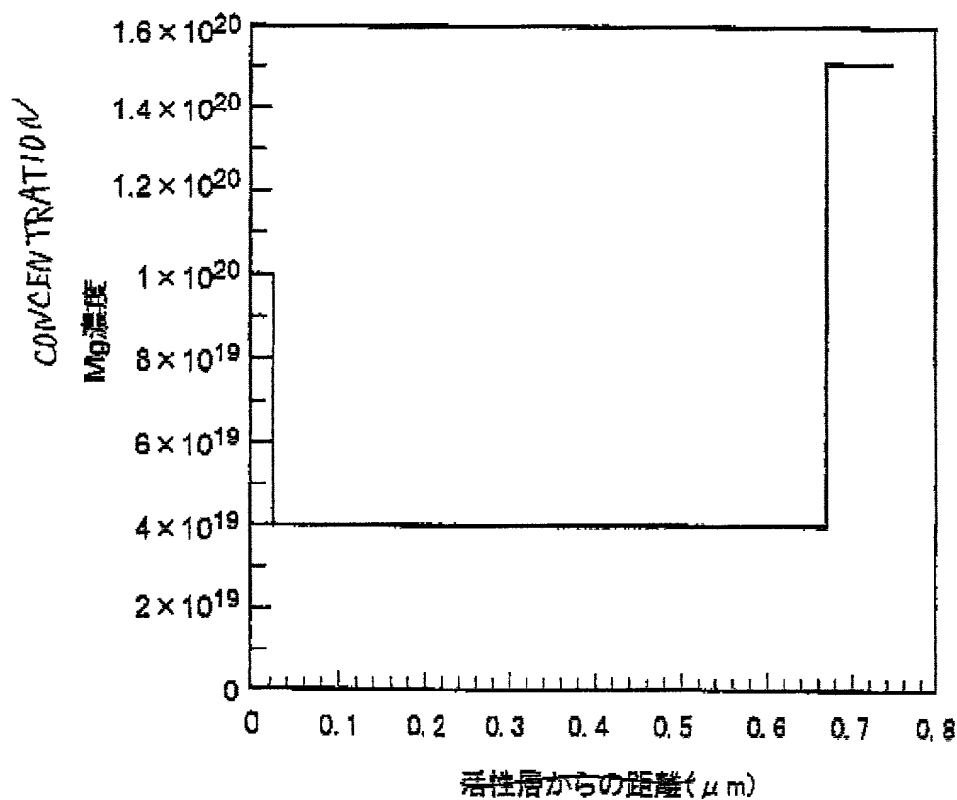
【図１８】　　　　　　　　　　FIG 17

本発明第6実施例の基礎となる実験結果を示す別の図

【図１９】

FIG18

本発明の第6実施例によるレーザダイオードで使われる
不純物分布を示す図



DISTANCE FROM ACTIVE LAYER

【図２０】

FIG19

図19の一変形例による不純物分布を示す図



図19の一変形例による不純物分布を示す図